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The nutrient film technique (NFT) is a unique modification of a hydroponic plant growth system which utilizes plants growing on an impermeable surface. A thin film of water flowing through the extensive root system provides nutrients for plants and associated microbial growth. Root masses up to 15 cm thick or more have been obtained. This self-generating plant system could be used as a filter to immobilize and use the gross and trace organics in wastewater. The goal of this study was to determine the economic, technical, and practical feasibility of using plants grown in the NFT system as pollution control systems.

NFT systems appear capable of providing secondary quality treatment with some nutrient removal on a relatively small area compared to overland flow systems. At loading rates of 10 cm per day the effluent quality with primary settled sewage was often less than 10 mg/l for suspended solids and biochemical oxygen demand. The influent sewage temperature was 9°C. Estimated area needs of an NFT system designed for BOD and SS removal appear to be approximately 3 hectares for a community of 10,000 people, whereas up to 10 times this amount may be needed to provide nutrient control.

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by

W. J. Jewell
J. J. Madras
W. W. Clarkson
H. DeLancey-Pompe
R. M. Kabrick

Department of Agricultural Engineering
Cornell University
Ithaca, New York 14853-0317

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Ada, Oklahoma 74820

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FOREWORD

EPA is charged by Congress to protect the Nation's land, air, and water systems. Under a mandate of national environmental laws focused on air and water quality, solid waste management and the control of toxic substances, pesticides, noise, and radiation, the Agency strives to formulate and implement actions which lead to a compatible balance between human activities and the ability of natural systems to support and nurture life. In partial response to these mandates, the Robert S. Kerr Environmental Research Laboratory, Ada, Oklahoma, is charged with the mission to manage research programs: to investigate the nature, transport, fate, and management of pollutants in ground water; to develop and demonstrate technologies for treating wastewater with soils and other natural systems; to control pollution from irrigated crop and animal production agricultural activities; and to develop and demonstrate cost-effective land treatment systems for the environmentally safe disposal of solid and hazardous wastes.

The nutrient film technique (NFT) is a unique modification of a hydroponic plant growth system which utilizes plants growing on an impermeable surface. This is the first comprehensive report on this unique plant production system which could lead to a new solar-powered pollution control/resource recovery system. It could serve as a major tool in achieving high water quality and resource recovery for the future. A thin film of water flowing through the extensive root system provides nutrients for plants and associated microbial growth in an NFT system. Root masses up to 15 cm thick or more have been obtained. This self-generating plant system could be used as a filter to immobilize and use the gross and trace pollutants in wastewater. The goal of this study was to determine the economic, technical, and practical feasibility of using plants grown in the NFT system as pollution control systems.

In general, the results show that the NFT would be highly competitive with existing secondary treatment alternatives and may significantly reduce the cost of tertiary treatment where high value plants can be grown and marketed. The NFT expands the choice of plants to all species to accomplish specific pollution control tasks. Roughing plants such as cattails may be chosen for use in secondary treatment, whereas ornamentals such as roses may be employed in tertiary treatment sections.

Clinton W. Hall, Director
Robert S. Kerr Environmental Research
  Laboratory

ABSTRACT

The present directions in wastewater treatment should emphasize maximum pollution control and the recovery of nutrients with minimum capital and energy investments. This is the first comprehensive report on a unique plant production system which could lead to a new solar-powered pollution control/resource recovery system. It could serve as a major tool in achieving high water quality and resource recovery for the future.

The nutrient film technique (NFT) is a unique modification of a hydroponic plant growth system which utilizes plants growing on an impermeable surface. A thin film of water flowing through the extensive root system provides nutrients for plants and associated microbial growth. Root masses up to 15 cm thick or more have been obtained. This self-generating plant system could be used as a filter to immobilize and use the gross and trace organics in wastewater. The goal of this study was to determine the economic, technical, and practical feasibility of using plants grown in the NFT system as pollution control systems.

Three parallel testing programs were used: pure substrate to define candidate species culturing practices and nutrient responses, synthetic wastewater, and primary settled domestic sewage. These three substrates allowed measurements of gross pollutant removal, as well as nutrient and trace organic removal kinetics. The three testing systems were operated at application rates of 2.5 to 40 cm per day, and flow rates of more than 11,000 liters per day. Major experimentation was conducted over a two-year period.

The successful cultural experiments have produced, from seed or cuttings, viable stands of reed canary grass, coastal bermuda grass, watercress, napier grass, and cattails in a maximum of six weeks. The propagation of several species in NFT units and their use in solar greenhouses that require little, if any, energy input anywhere in the U.S. have been successful. Many species were screened to identify their possible roles in NFT systems, and several plants or plant types were found to perform well in the various parts of an NFT treatment system.

Although the NFT systems evapotranspired large quantities of water, energy costs for the recovery of this high quality water were prohibitive for the recovery systems examined.

NFT systems appear capable of providing secondary quality treatment with some nutrient removal on a relatively small area compared to overland flow systems. At loading rates of 10 cm per day the effluent quality with primary settled sewage was often less than 10 mg/ℓ for suspended solids and biochemical oxygen demand. The influent sewage temperature was 9°C. Estimated area needs of an NFT system designed for BOD and SS removal appear to be approximately 3 hectares for a community of 10,000 people, whereas up to 10 times this amount may be needed to provide nutrient control. Empirical relationships for the removal of nutrients and contaminants were developed, and would be useful in designing an NFT system for domestic sewage. Attempts to summarize the results in a kinetic model were generally unsuccessful. The system also proved effective in removing heavy metals and trace organics from wastewater.

These area requirements for secondary treatment would result in a cost-competitive system without taking advantage of any of the reduced operation costs or commercial benefits of plant production. The area requirement for tertiary treatment indicates that the NFT would not be competitive with conventional technologies unless plant products have a commercial value.

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CONTENTS

Page

Foreword iii
Abstract iv
Figures xi
Tables xx
Abbreviations and Symbols xxiv
Acknowledgment xxv

I. INTRODUCTION 1

A. Goals and Objectives 1
B. Basic Concept and Purpose of the System 2
C. Hypothesized Nutrient Film Wastewater Treatment System 2
D. Similarity with Other Treatment Systems and Adaptation of Hydroponic Systems 4
E. Limitations to the NFT Wastewater Treatment. 6

II. CONCLUSIONS 7

III. RECOMMENDATIONS. 12

A. Additional Species Screening and Parametric Evaluation 12
B. Pollutant Removal Mechanisms 12
C. Aeration Due to Capillary Mat in Reed-type Plants. . . 12
D. Lower Nutrient Effects on Yield. 13
E. ET Recovery. 13
F. Drinking Water and Polishing Applications. 13
G. Nitrogen Cycle Manipulation With the NFT 13
H. Scale-up of Optimum NFT Systems. 13

IV. BACKGROUND AND LITERATURE REVIEW 14

A. Hydroponics 16
B. Wastewater and Water Treatment in Hydroponic Systems . 18
C. Plant Physiology and Morphology Implications 22
C.1. Redox Potential and the Effect of Sewage Film on the Plant Root Environment 23
C.2. Physiological Implications of Growth in Sewage Film 25
C.2.a. Plant Response to Anaerobiosis 25
C.2.b. Exogenous Phytotoxins 28
C.2.c. Plant Growth in Sewage Compared to Natural Habitats 33

Page

C.3. Plant Adaptation to Sewage 37
  C.3.a. Mechanisms of Adaptation 37
  C.3.b. Indicators of Adaptation to Anaerobic Conditions 40
  C.3.c. Identification of Plants Tolerant to NFT Sewage Environment. 41
C.4. Environmental Factors Affecting Tolerant Plants . 41
  C.4.a. Effect of Water Level on Growth of Emergents. 41
  C.4.b. Effects of Temperature on Emergents 49
  C.4.c. Light Intensity 50
  C.4.d. Photoperiod 51
C.5. Plant Growth Characteristics 51
  C.5.a. Assimilation of Nutrients and Yield 51
  C.5.b. Release of Organic Carbon by Emergents . . . 55
  C.5.c. Life Histories 58
  C.5.d. Effects of Harvesting Yield and Chemical Composition 58
  C.5.e. Regeneration and Reproduction 58
C.6. Metabolic Activity of Bacteria on Roots 59

V. SCOPE AND METHODOLOGY 60

A. Participants in the Project 60
B. Methods to Meet the Project's Objectives 60
C. Phase 0 Activities 61
  C.1. Cornell University. 61
  C.2. New Hampshire 64
  C.3. General Electric 64
D. Phase 1 Activities 64
  D.1. Cornell University 64
  D.2. CRREL 65

VI. MATERIALS AND METHODS 66

A. Process Definition with Synthetic Sewage--Studies at Ithaca, New York 66
  A.1. Synthetic Sewage Composition. 66
  A.2. Pilot Scale Units (Bracehouse) 69
    A.2.a. Brace greenhouse and test units 69
    A.2.b. Loading Rate Schedule and Plant Species Tested 79
    A.2.c. Root Analysis 83
  A.3. Bench Scale Units 86
    A.3.a. Ken Post Greenhouse and Test Units 86
    A.3.b. Loading Rates Schedule and Plant Species Tested 89
  A.4. Analytical Methods 91

Page

B. Process Definition with Sewage--Studies at Hanover, NH, and Cayuga Heights, NY. 93
B.1. Pilot Scale Units 93
B.1.a. CRREL Greenhouse and Test Units 93
B.1.b. CRREL Loading Rates Schedule 96
B.1.c. Hanover Greenhouse and Test Units 98
B.1.d. Hanover Loading Rates Schedule and Plant Species Tested. 104
B.1.e. Root Analysis 105
B.1.f. CRREL Analytical Procedures 105
B.2. Bench Scale Units 105
B.2.a. Hanover Bench Scale Units and Experiment Schedule 105
B.2.b. Cayuga Heights Greenhouse, Bench Scale Units and Experiment Schedule 107
B.3. Comparison of Synthetic and Actual Domestic Wastewater 113
C. Testing Approach 116
C.1. Parameter Evaluation 116
C.2. Season, Temperature and Environmental Controls . 116
C.3. Test Parameters and Duration 117
C.4. Loading Rate Characterization 118
D. Plant Considerations 125
D.1. Plant Selection Criteria 125
D.2. Species Tested 132
D.3. Culturing Considerations. 133
D.3.a. Obtaining Plant Material 133
D.3.b. Growing Plant Material 137
D.4. Plant Care During Crisis 138
E. Analytical Approach 138
E.1. Computerized Summary of Information 138
E.2. Long-term Analysis 138
E.3. Sensitivity of System to Controlling Parameters . 139
E.4. Formulation of Predictive Relationships 139

VII. RESULTS 140

A. Chronological Development of Treatment Capacity of NFT Systems 141
B. Characteristics of the NFT in Treating Synthetic Wastewater and Domestic Sewage 147
B.1. pH 147
B.2. Dissolved Oxygen 151
B.3. Temperature 154
B.4. Suspended Solids 154
B.5. Turbidity 156
B.6. Chemical Oxygen Demand 156
B.7 Nitrogen 163
B.8. Phosphorus. 163

Page

B.9. Indicator Organisms 169
B.10. Zinc and Cadmium 169
C. Process Sensitivity and Pollutant Removal Mechanism Definition 169
C.1. Hydraulic Retention Time Effects 169
C.2. Loading Rates Effects 173
C.3. Loading Rate Relationships with Synthetic Wastewater 176
C.4. Primary Settled Domestic Sewage Loading Rates Effects 180
C.5. Plant Environmental Factors 196
C.5.a. Temperature 198
C.6. Root Mass Influence 198
C.7. Bench Scale Simulation 199
C.8. Experiments with Recirculating Bench Scale Models 201
C.9. Domestic Sewage, Bench Scale Test 207
C.10. Testing of Optimized Design 211
D. Water Balance and Energy Transfer 215
D.1. ET Rates. 216
D.2. ET Recovery Systems 219
D.2.a. Necessary Cooling Capacity 220
D.2.b. Air-to-air heat exchanger 220
D.2.c. Refrigerative Dehumidification 224
D.3. Economic Considerations 225
D.4. Alternative Approaches for Condensation 225
E. Nutrient Uptake 225
F. Plant Culturing and Propagation for Establishing and Operating an NFT System 236
F.1. Culture of Species in Total Controlled Environments 236
F.1.a. Nutrient Removal in Total Controlled Environmental Greenhouses 237
F.1.b. Biomass Production 237
F.2. Culture of Species in Greenhouses 245
F.2.a. Response to Non-carbonaceous Nutrient Solution 245
F.2.b. Plant Response to Sewage in NFT Systems . . . 249
F.3. Diagnosing and Treating Plant Growth Problems . . 257
G. Toxic Constituent Considerations--Cadmium and Toxic Organics (Volatile and Nonvolatile) 262
H. Comparison of Synthetic and Domestic Sewage in NFT Systems 262
I. Development of Predictive Relationships 267

VIII. DISCUSSION 281

A. General Considerations. 281

Page

  B. NFT Characteristics and Pollutant Removal Mechanisms 282
    B.1. Settling, Filtration, and Suspended Solids Control 282
    B.2. Microbial Metabolism and BOD and COD Removal . . . 284
    B.3. Nutrient Removals 285
  C. Toxic Substances 288
  D. TDS Manipulation 288
  E. Temperature Effects 290
  F. Process Sensitivity and Design 290
  G. Plant Environment Factors 291
  H. Optimized Facility Considerations 292
  I. Plant Culturing and Propagation 293

IX NFT TOTAL SYSTEM FEASIBILITY CONSIDERATIONS 295

  A. The NFT As a Secondary Treatment System 295
  B. The NFT As a Tertiary Treatment Facility 298

REFERENCES 300

APPENDICES

  A. General Electric Phase 0 Data 312
  B. Hanover, New Hampshire, Data 315
  C. Cornell University Data 392

FIGURES

Number		Page
1.1	The nutrient film technique variation of hydroponic plant production systems	3
1.2	Schematic diagram showing three-stage hypothesized NFT treatment system for domestic wastewater with functions for each stage and fate of all materials	5
4.1	Plymouth, England, research group facilities	19
4.2	Approximate critical thresholds for stability of redox systems	24
4.3	Summary of physiological effects of the flooded root zone	29
4.4	Aboveground nitrogen content of emergent aquatic plants .	53
4.5	Aboveground phosphorus content of emergent aquatic plants	54
4.6	Peak aboveground biomass of emergent aquatic plants in natural habitats	56
4.7	Peak belowground biomass of emergent aquatic plants in natural habitats	57
5.1	Chronology of major events and testing periods of the NFT project	62
5.2	Different NFT systems at Cornell University, General Electric Company Syracuse facility, and at CRREL in Hanover, New Hampshire.	63
6.1	The Cornell Brace-style solar greenhouse	70
6.2	Schematic diagram of basic Cornell NFT experimental unit.	72
6.3	Standard NFT tray	73
6.4	Section view of NFT tray, sampling ports, and adjustable support structure	74

Number Page

6.5 Level unit that can withstand flooding. 75

6.6 View of interior of Cornell solar greenhouse showing NFT trays emptry and containing reed canary grass 75

6.7 Schematic diagram of the influent distribution box. . . . 77

6.8 View of synthetic wastewater mixing and distribution system. 78

6.9 Schematic diagram of three-part 36.6 meter system at Hanover containing several species 81

6.10 Schematic diagram of Bracehouse 36.6 meter multi-species unit 82

6.11 Root sampling devices: (a) cattail, bulrush and phragmites, (b) reed canary grass 84

6.12 Post House 3 meter (10 ft) units in operation 87

6.13 Construction of 3 meter (10 ft) units in Post House . . . 87

6.14 Schematic of Post House 1.5 meter (5 ft) unit 88

6.15 Post House 1.5 meter (5 ft) unit in operation 88

6.16 Superstructure and plywood covered floor schematics of 5.1 meter (20 foot) portable units. 90

6.17 Experimental NFT unit for primary settled domestic sewage studies at CRREL 94

6.18 View of initial placement of reed canary grass washed sod just after the first harvest at CRREL 94

6.19 Schematic diagram of the CRREL NFT system 95

6.20 Site plan of greenhouse and Hanover, New Hampshire, sewage treatment plant 99

6.21 Attachment of trusses to posts during construction of the Hanover greenhouse. 101

6.22 View of the plastic covered Hanover greenhouse, treatment plant building, and surrounding grounds 101

6.23 Schematic diagram of units in the Hanover greenhouse. . . 102

6.24 The interior of the Hanover greenhouse showing the NFT trays under construction. 103

Number		Page
6.25	Test unit used in the high loading rate experiments using domestic sewage at the Cayuga Heights treatment plant	109
6.26	Napier grass used in high loading experiments at the Cayuga Heights treatment plant.	110
6.27	Schematic diagram of experimental system used for high loading rate experiments at the Cayuga Heights treatment plant	111
6.28	Plastic shelter and enclosed units at the Cayuga Heights, New York, treatment plant	112
6.29	Hydrograph for 36.6 meter Bracehouse pilot system on 4-27-81 (10.2 cm per day, loaded during first 7.5 minutes of each half hour)	122
6.30	Direct measurement of flow entering and leaving various units in Bracehouse system on May 27, 1981.	123
6.31	Relation between the number of species included in an end product and the relative value of that end product. .	131
6.32	Stand of phragmites at Montezuma Wildlife Refuge.	134
6.33	White canary grass roots forming a root mat below capillary matting used in seeding trials.	136
6.34	Napier grass, sugar cane and cottonwood cuttings after placement in the NFT 3 meter units.	136
7.1	Influent and effluent chemical oxygen demand for the Cornell NFT treating synthetic wastewater in spring 1981	142
7.2	Chronological data development for Cornell Phase I (1981) studies with reed canary grass NFT units	143
7.3	Influent and effluent chemical oxygen demand for the Hanover NFT treating domestic wastewater in spring 1981 .	144
7.4	Example of chronological data development for domestic sewage testing with the NFT at Hanover, New Hampshire . .	145-146
7.5	Incident radiation and yield of reed canary grass grown in continuing NFT culture in the Cornell Bracehouse over the course of experimentation	148-150
7.6	Dissolved oxygen concentration in reed canary grass NFT treating synthetic wastewater	152

Number Page

7.7 Dissolved oxygen concentration in multispecies NFT unit treating primary settled domestic sewage at Hanover, New Hampshire 153

7.8 Mean suspended solids concentrations in NFT systems treating domestic wastewater at 10.2 cm/d 155

7.9 Reductions of total and soluble chemical oxygen demand concentrations in synthetic wastewater through 12 m and 36 m systems. 157

7.10 Chemical oxygen demand removal efficiency at different stages of stand maturity and under different mean temperatures 158

7.11 Influence of system length on soluble COD removal from synthetic sewage at an area loading rate of 20.3 cm/d . . 159

7.12 Reductions of total and soluble chemical oxygen demand concentrations in domestic sewage in 36 m multiple species NFT units, which were tested at three different loading rates 160

7.13 Total and soluble oxygen demand concentration at various points in 36 m multiple species unit treating domestic wastewater. Three loading rates are shown. 161

7.14 Comparison of COD removal from domestic sewage during relatively warm and cold temperatures 162

7.15 Total nitrogen concentration of synthetic wastewater in three different NFT systems at an area loading rate of 10 cm/d 164

7.16 Total Kjeldahl nitrogen concentration reductions in 9.3 m^2 reed canary grass units using synthetic wastewater. . . . 165

7.17 Ammonia nitrogen concentrations of synthetic sewage at various sampling points in NFT systems. 166

7.18 Total phosphorus concentrations of synthetic wastewater in different length systems 167

7.19 Total phosphorus concentrations of domestic sewage at different loading rates to two systems. 168

7.20 Influent and effluent concentrations of phosphorus in domestic sewage in the Hanover NFT system, which began operation on February 16, 1981. 170

Number Page

7.21 Influent and effluent zinc concentrations of synthetic sewage in a reed canary grass pilot scale unit. First day of analysis was July 25, 1980 171

7.22 Influent and effluent zinc concentrations of synthetic sewage in a reed canary grass pilot scale unit. First day of analysis was July 25, 1980 172

7.23 Hydraulic retention times of a 36 m NFT system using synthetic wastewater 174

7.24 Hydraulic retention time of the 36 m system using domestic wastewater loaded at 10.2 cm/d 175

7.25 Relationship between total COD removal efficiency and total COD mass loading rate for conditions tested with synthetic sewage 177

7.26 Relationship between total COD mass loading rate and total COD mass removal in the NFT systems treating domestic sewage 178

7.27 Relationship between soluble COD mass loading rate and soluble COD mass removal in the NFT systems treating synthetic sewage. 179

7.28 Relationship between total nitrogen removal efficiency and total nitrogen mass loading rate for conditions tested with synthetic sewage. 181

7.29 Relationship between soluble nitrogen removal efficiency and soluble nitrogen mass loading rate for conditions tested with synthetic sewage. 182

7.30 Relationship bewteen total phosphorus removal efficiency and total phosphorus mass loading rate for conditions tested with synthetic sewage. 183

7.31 Relationship between soluble phosphorus removal efficiency and soluble phosphorus mass loading rate for conditions tested with synthetic sewage. 184

7.32 Relationship between BOD removal efficiency and BOD mass loading rate for conditions tested with domestic sewage . 185

7.33 Relationship between BOD mass loading rate and BOD mass removal in the NFT systems treating domestic sewage . . . 186

7.34 Relationship between TOC removal efficiency and TOC mass loading rate for conditions tested with domestic sewage . 187

Number		Page
7.35	Relationship between TOC mass loading rate and TOC mass removal in the NFT systems treating domestic sewage. . . .	188
7.36	Relationship between suspended solids mass loading rate and suspended solids mass removal in the NFT systems treating domestic sewage	189
7.37	Relationship bewteen volatile suspended solids mass loading rate and volatile suspended solids mass removal in the NFT systems treating domestic sewage.	190
7.38	Relationship between nitrogen mass loading rate and nitrogen mass removal for conditions tested with domestic sewage	191
7.39	Relationship between phosphorus mass loading rate and phosphorus mass removal for conditions tested with domestic sewage.	192
7.40	Effect of temperature on the treatment efficiency of BOD and TOC in NFT systems using domestic sewage	193
7.41	Effect of temperature on the treatment efficiency of total and volatile suspended solids in NFT systems using domestic sewage.	194
7.42	Effect of temperature on the treatment efficiency of nitrogen and phosphorus in NFT systems using domestic sewage	195
7.43	Healthy canary grass in Unit 3, Bracehouse	197
7.44	Brown canary grass in Unit 3, Bracehouse	197
7.45	Hydraulic retention times in the bench scale varied flow experiment using synthetic wastewater	202
7.46	Hydraulic volume contained in bench scale varied flow units at different loading rates of domestic sewage . . .	203
7.47	Total and soluble COD concentrations of the influent and effluent synthetic wastewater to a reed canary grass bench scale unit loaded at 20 cm/d	204
7.48	Effluent biochemical oxygen demand concentrations of different units in the varied flow experiment, which began July 20, 1981	205
7.49	Comparison of evapotranspiration from bench scale units. .	206

Number		Page
7.50	Effluent phosphorus concentrations from the control and napier grass units in an early bench scale experiment using a recirculating solution. The experiment began on February 27, 1981	208
7.51	Effluent phosphorus concentrations from the control and napier grass units in a later bench scale experiment using a recirculating solution. The experiment began on April 8, 1981	208
7.52	Effluent total nitrogen concentrations of synthetic sewage from bench scale units containing several plant species. This series of experiments began March 18, 1981.	209
7.53	Relationship between area loading rate and removal of solids and BOD in bench scale NFT systems using synthetic sewage	210
7.54	Effluent biochemical oxygen demand concentrations of units at different loading rates in the varied flow experiment using domestic sewage. The experiment started on June 22, 1981	212
7.55	Biochemical oxygen demand concentrations over time in recirculating domestic sewage units containing different plant species	213
7.56	Schematic energy balance for a hypothetical greenhouse in January and July in Ithaca, New York	221
7.57	Condensation temperature and cooling capacity necessary to recover all ET vapor as a function of mass flow rate of air	222
7.58	Configuration of the air-to-air heat exchanger used in design estimates	223
7.59	Energy balance for the refrigerative compression system .	226
7.60	Dry weight harvest yield of a 9.3 m^2 reed canary grass control unit	227
7.61	Plant seedlings growing on mat in NFT trough	238
7.62	Growth of watercress before biweekly harvest. Plants grew to 20 cm above bed floor.	238
7.63	Stand of watercress after biweekly harvest	239
7.64	Stand of reed canary grass grown from plugs.	239

Number Page

7.65 Napier grass cutting at initial transplant into the NFT trough 240

7.66 Napier grass stand at time of move to larger bed 240

7.67 Regrowth of napier grass three weeks after first harvest 241

7.68 Side view of root mats of reed canary grass, coastal Bermuda grass, and watercress grown in NFT trough. . . . 241

7.69 Bottom view of root mats of reed canary grass, coastal Bermuda grass, and watercress grown in NFT trough. . . . 242

7.70 Side view of root mats of cattails and napier grass grown in NFT trough. 242

7.71 Bottom view of root mats of cattails and napier grass grown in NFT trough. 243

7.72 Nitrogen and phosphorus removals from General Electric NFT unit containing reed canary grass. 244

7.73 Cattail, bulrush, phragmites, and canary grass growing well in the Bracehouse 36.6 meter system 250

7.74 Root zone of a rose in peat pot showing anoxic accumulations at bottom. 252

7.75 Hanover unit containing cucumbers during early testing of the large unit. 254

7.76 Poor root development of cucumber after a month in the NFT unit in the Hanover greenhouse 254

7.77 Schematic diagram of second system in Hanover greenhouse showing locations of plants relative to sewage flow . . 256

7.78 Black root zone below dead reed canary grass 258

7.79 Geranium plant showing new root growth after old roots had rotted in peat pot 258

7.80 Chrysanthemum and peat pot showing absence of roots due to root death 259

7.81 Larval gnats in connecting gutter between trays at the Hanover greenhouse 261

7.82 Cadmium concentrations at various points in three different length systems, the longest of which contained several species. 264

Number Page

7.83 Comparison of synthetic and domestic sewage variables in 27.9 m^2 units operated at an area loading rate of 10.2 cm/d 266

7.84 Comparison of chemical oxygen demand reductions in domestic and synthetic sewage at various loading rates in 27.9 m^2 units. 268

7.85 Rate determination plot for BOD removal from domestic sewage by a canary grass system 273

7.86 Rate determination plot for suspended solids removal from domestic sewage by a canary grass system 274

7.87 Rate determination plot for volatile suspended solids removal from domestic sewage by a canary grass system . . 275

7.88 Rate determination plot for total nitrogen removal from domestic sewage by a canary grass system 276

7.89 Rate determination plot for total phosphorus removal from domestic sewage by a canary grass system 277

7.90 Rate determination plot for COD removal from synthetic sewage by canary grass units in different size systems. . 278

7.91 Rate determination plot for phosphorus removal from synthetic sewage by canary grass units in different size units. 279

7.92 Rate determination for total nitrogen removal from synthetic sewage in canary grass units of different areas 280

8.1 Photograph of the effluent from an NFT unit treating primary settled sewage showing the large coagulated particles settled in the overflow trough 286

8.2 Relationship of plant yield to land area required for complete nitrogen removal from domestic sewage for crops with two different levels of nitrogen 287

8.3 Calculated maximum total dissolved salts removal efficiency with plants in the NFT at varying yields . . . 289

9.1 Schematic of NFT treatment facility capable of treating domestic sewage from 10,000 people. 296

TABLES

Number		Page
4.1	State of the Art Characteristics of Aquatic Systems and Land Application Systems Used for Domestic Sewage Treatment	15
4.2	Plant Characteristics Important for Wastewater Treatment Mechanisms in an NFT System	22
4.3	Potentially Toxic Elements Found in Residential Trunk Sewers	30
4.4	Essential Minerals for Higher Plants	30
4.5	Amounts of Cadmium Absorbed by Various Plant Species in Relation to Solution Cadmium Concentration	31
4.6	Concentration of Fly Ash Pollutants Absorbed by Aquatic Plants	32
4.7	Solution Cd Concentrations Producing 50% Growth Reduction, Visual Symptoms Associated with 50% Growth Reduction, and Concentration in Leaf at 50% Growth Reduction	33
4.8	Effect of Heavy Metals in the Nutrient Solution on Growth of Floating or Submergent Aquatic Plants	34
4.9	Potential Phytotoxicity of Hydrocarbons and Other Organic Compounds	36
4.10	Plant Adaptations to Survive an Anoxic Environment. . . .	38
4.11	Emergent Species Tolerant or Potentially Tolerant to NFT Sewage Environment.	42
4.12	Organic Matter Content of Some Emergents.	52
6.1	Dry Chemical Constitutents in Concentrated Feed Stock and Synthetic Sewage.	67
6.2	Phase 0 Testing Schedule for the Brace House 12.2 meter (40 foot) Canary Grass Unit	79
6.3	Phase 1 Schedule for the Brace House 12.2 meter (40 foot) and 24.4 meter (80 foot) Canary Grass Units	80

Number Page

6.4 Testing Schedule for the Cornell 36.6 meter (120 foot) Multispecies System 83

6.5 Cornell Bench Scale Experiments Conducted in the Glass Covered Greenhouse (Ken Post Laboratory) 91

6.6 Summary of CRREL Study Activities in the 12.2 m Pilot Scale System During Phase 0 97

6.7 Loading Conditions Tested in the 12.2 m Pilot Scale System in the CRREL Greenhouse During Phase 1 98

6.8 Loading Conditions Tested in the Pilot Scale Unit at the Hanover Treatment Plant 104

6.9 Hanover Greenhouse Bench Scale Experiments 106

6.10 Schedule of Experimental Conditions at Cayuga Heights . . 113

6.11 Characteristics of Influent Synthetic and Real Sewage . . 115

6.12 Test Parameters and Duration of the Cornell Pilot Scale Systems Using Synthetic Sewage 117

6.13 Test Parameters and Duration of the CRREL and Hanover Pilot Scale Systems Using Domestic Sewage 118

6.14 Comparison of Loading Rate Parameters for Synthetic Sewage 120

6.15 Typical Hydraulic Characteristics of a 36.6 m Long (27.9 m^2) Pilot Scale NFT Unit as Estimated from Water Depth Measurements During Operation of the Unit 124

6.16 Comparison of Retention Times (in Minutes) in 27.9 m^2 Pilot Scale Units Operating at Different Conditions with Real and Synthetic Wastewater 126

6.17 Favorable Plant Characteristics for Treatment of Wastewater in NFT Systems. 127

6.18 Plants Grown in NFT Units or Examined for Cultural Properties During the Study 132

6.19 Collection Data from Wetland Plants Grown in the NFT . . 133

6.20 Volunteer Species Which Survived Transplanting with Other Wetland Species 135

6.21 Sources and Propagules of Commercial Plants Grown in NFT Units 137

Number		Page
7.1	Variables Measured in Testing Pilot Scale NFT Systems With Synthetic and Domestic Sewage	151
7.2	Range of Pollutant Loading Rates Tested With Synthetic Sewage in Pilot NFT Units.	176
7.3	Range of Pollutant Loading Rates Tested With Domestic Settled Sewage in Pilot NFT Units	196
7.4	Total and Volatile Accumulations of Materials in the Roots of Plants Tested in 27.9 m^2 Pilot Units Using Synthetic and Domestic Wastewater	199
7.5	Total and Volatile Entrapped Solids in the Root Zone of Plants Tested in 27.9 m^2 Pilot Units Using Synthetic and Domestic Wastewater	200
7.6	Summary of Optimized Operation of the NFT as a Primary and Secondary Combined Treatment System Using Intermittently Loaded and Unloaded Plants. Experiments Were Conducted at the Cayuga Heights Village Treatment Facility	214
7.7	Evapotranspiration of the 9.3 m^3 Reed Canary Grass Unit of the Cornell Bracehouse. Data Were Collected During the Testing of the 27.9 m^2 Multispecies System in the Same Greenhouse in 1981.	216
7.8	Comparison of Evapotranspiration Between a Canary Grass Pilot Scale Unit and Bench Scale Units Containing Different Plant Species at Cornell Using Nutrient Solution or Synthetic Sewage	217
7.9	Comparison of Evapotranspiration Between a 27.9 m^2 Pilot Scale System and Bench Scale Units Containing Different Plant Species Using Domestic Sewage	218
7.10	Dates, Yields, Dry Weights and Nutrient Contents of Aged Canary Grass Harvests in the Cornell Bracehouse Unit #2	228
7.11	Dates, Yields, Dry Weights and Nutrients Contents of Reed Canary Grass Harvests in the Cornell Brace House Unit #4	230
7.12	Dates, Yields, Dry Weights and Nutrients Contents of Reed Canary Grass Harvests in the Cornell Bracehouse Unit #3	232
7.13	Harvest Data from the CRREL Greenhouse Which Grew Canary Grass in 7.4 m^2 Units (Total)	234

Number		Page
7.14	Harvest Data from Hanover Greenhouse in 1981	236
7.15	Grass Nutrient Formula Used in Plant Propagation in Total Controlled Environment	245
7.16	Biomass Yield of Test Species Shoot Harvest	245
7.17	Plant Response to Nutrient Solutions	247
7.18	Plant Response to Sewage	249
7.19	Reed Canary Grass Pathologies and Treatments	257
7.20	Fate of Cadmium in NFT Pilot Systems at Cornell	263
7.21	Trace Organic Concentrations in Sewage in the Hanover NFT System	265
7.22	System Performance Summary of Pilot Scale Systems Using Synthetic Sewage	269
7.23	System Performance of Pilot Scale Systems Using Domestic Sewage	270
7.24	Comparison of Mean Mass Removals from Synthetic and Domestic Sewage in Pilot Scale Systems	271
7.25	Summary of Substrate Removal Coefficients as Determined from Assumed first Order Kinetic Estimates for Canary Grass Systems	272
8.1	Advantages and Disadvantages of the NFT System When Used for Wastewater Treatment	282
9.1	Summary of Comparison of Two Secondary Treatment Technologies Compared to an NFT System	297
9.2	Estimated Water Quality to be Produced by the Proposed Water Reclamation Facility	299

ABBREVIATIONS AND SYMBOLS

BOD	biochemical oxygen demand
$CaCl_2$	calcium chloride
$Ca(NO_3)_2$	calcium nitrate
Cd	cadmium
$CdSO_4$	cadmium sulfate
cm	centimeter
CO_2	carbon dioxide
COD	chemical oxygen demand
CRREL	Cold Regions Research and Engineering Laboratory
d	day
DO	dissolved oxygen
ET	evapotranspiration
ETP	potential evapotranspiration
FC	fecal coliform
Fe	iron
Fe^{+2}	ferrous iron
FSS	fixed suspended solids
g	gram
ha	hectare
HRT	hydraulic retention time
H_2S	hydrogen sulfide
J	joule
JTU	Jackson turbidity unit
K	potassium
kg	kilogram
K_2HPO_4	potassium phosphate dibasic
KH_2PO_4	potassium phosphate monobasic
kJ	kilojoule
kw	kilowatt
kwh	kilowatt hour
ℓ	liter
LR	loading rate
m	meter
MEQ	milliequivalent
MGD	million gallons per day
mℓ	milliliter
mg/ℓ	milligrams per liter
mm	millimeter
Mn^{+2}	manganese
Mn^{+4}	manganese
μg	microgram
mV	millivolts
N	nitrogen
NaCl	sodium chloride
NH_3	ammonia nitrogen
NO_3^-	nitrate nitrogen
O_2	oxygen
OM	organic matter
P	phosphorus
Pb	lead
pCO_2	partial pressure of CO_2
PO_4^{-3}	orthophosphate phosphorus
ppb	parts per billion
ppm	parts per million
RBC	rotating biological contactor
RCG	reed canary grass
sec	second
SOL	soluble
SS	suspended solids
Std. Dev.	standard deviation
t	tonne
TFS	total fixed solids
TKN	total Kjeldahl nitrogen
TN	total nitrogen
TOC	total organic carbon
TP	total phosphorus
TSS	total suspended solids
TVS	total volatile solids
VSS	volatile suspended solids
wk	week
yr	year
Zn	zinc
$<$	less than
$>$	equal to or greater than
$\simeq$	approximately equal to

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CHAPTER I

INTRODUCTION

The U.S. wastewater management program emphasizes systems that require minimum capital and energy and recover resources such as nutrients and water. The U.S. Environmental Protection Agency has made significant efforts to encourage land treatment and other innovative systems that support mandates issued by Congress. Similarly, the U.S. Department of the Interior has fostered water conservation and reuse. The soilless culture plant production system described here has potential to aid in these pursuits. This modification of a hydroponic system, called the Nutrient Film Technique (NFT), has been developed and tested at significant "proof-of-concept" scale applications.

A. GOALS AND OBJECTIVES

There is increasing interest in the use of low-cost natural systems that have existing or built-in pollution control mechanisms. This project focuses on a new plant production system that could lead to new ways of treating wastewater and water supplies with a self-generating pollution control system that could have a number of useful and valuable by-products. The main goal of this feasibility study was to:

> *determine the feasibility of using plants as pollutant-concentrating, pollutant-assimilating and nutrient-recycling facilities in a unique hydroponic system utilizing the Nutrient Film Technique.*

The five specific objectives were to:

1. define advantages of using plants in the Nutrient Film Technique system over conventional systems to collect, concentrate, and assimilate pollutants;

2. identify research and dvelopment needs to support a long-term program to define the full potential of the Nutrient Film Technique system as a pollutant management/resource recovery system;

3. define the engineering requirements to establish a total plant-based pollutant control system. This will include area requirements, hardware, plants and plant production systems;

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4. gather baseline data on system performance using energy and mass balance to support econometric data;

5. determine the feasibility of recovering energy, food, and nutrients from the plant material.

The NFT system presents opportunities for tailoring a specific plant system to the treatment job to be accomplished through the choices of plant selection and system configuration. Design parameters were developed based on hydraulics and removal of nutrients, organics, trace organics and cadmium. Plant selection and management methods were investigated and are described. Finally, the potential evapotranspiration (ET), actual ET and recovery of ET are discussed.

B. BASIC CONCEPT AND PURPOSE OF THE SYSTEM

The nutrient film technique (NFT) is a unique modification of a hydroponic plant growth system. The NFT version of hydroponics utilizes plants grown directly on an impermeable surface to which a thin film of water is continuously applied (see Figure 1.1). The root production on this impermeable surface will result in a large mass of roots and accumulated matter with a large surface area. Root masses have been observed to accumulate up to 30 cm deep, separate from the stalk and fruit. The hypothesis here is that these large masses of self-generating root systems can be used as living filters. Plant top growth also provides nutrient uptake, shade for protection from algae, and water removal in the form of transpiration. Sludge that would settle in the root filter would be held in place by the roots, and the filter itself would gradually expand as the sludge accumulated and occupied more space. After removal of organics and suspended solids, the remaining refractory soluble organics, nutrients, and remaining toxic elements would continue to pass through the fine root filter. Since high flow rates are possible in the absence of large amounts of suspended and organic matter, subsequent loading rates would be related to the sorption rates of critical wastewater constituents such as nutrients. This general interaction of pollutants, plants and water leads to a general description of a hypothesized wastewater treatment system as discussed in the next section.

C. HYPOTHESIZED NUTRIENT FILM WASTEWATER TREATMENT SYSTEM

The fate of pollutants and the accumulation of sludge in an NFT leads to a definition of plant requirements and eventually to the potential of a solar powered treatment system purifying waters. The hypothesized system would be composed of three distinct sections:

1. Roughing or Preliminary Treatment: Plant species with large root systems capable of surviving and growing in a grossly polluted condition. Large sludge accumulations, anaerobic conditions, and trace metal precipitation and entrapment would characterize this section. A large portion of the BOD_5 and SS would be removed in this section.

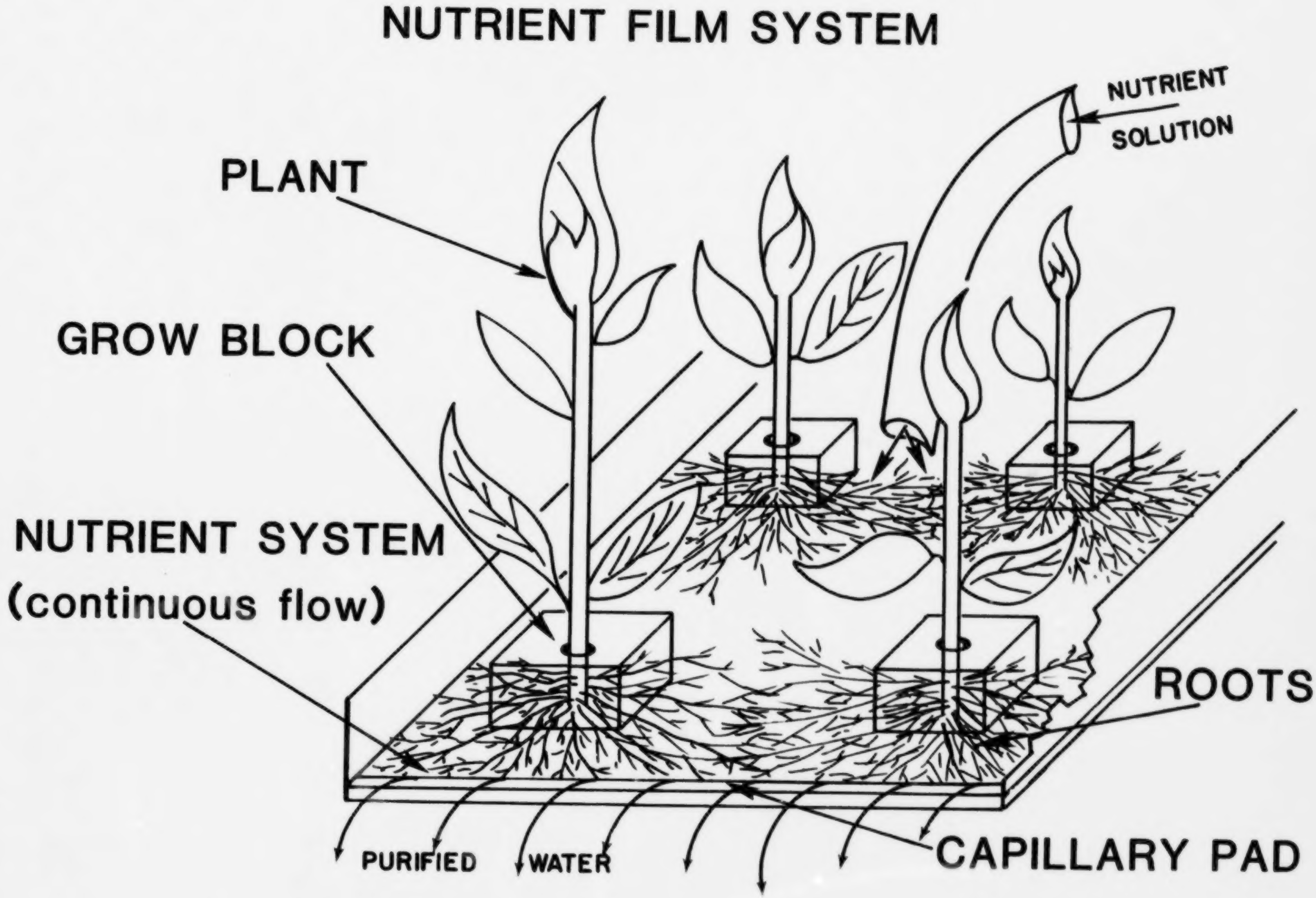


Figure 1.1. The nutrient film technique variation of hydroponic plant production systems.

2. Nutrient Conversion and Recovery: An active nutrient uptake, high biomass and/or food production section would follow the first section. The major interaction here would be nutrient conversions, but suspended solids and trace organic removals would improve.

3. Water Polishing: The third section would be a polishing section that would necessarily have nutrient-limited plant production, depending on the required effluent water quality.

A schematic of the three plant series wastewater treatment system, showing the major pollution control functions and the by-products produced in each section, is presented in Figure 1.2.

Obviously, the three modules in the NFT treatment system can also be used separately for different levels of treatment of varying input water quality. For example, the system may be applicable to polishing secondary effluents or lagoon effluents. Testing to define the last section has the potential of producing an effluent relatively free of trace organics and nutrients. In essence, a modification of this section may result in a viable alternative to the activated carbon adsorption unit process for water supply treatment. It may also be used to improve the bacterial quality of sewage effluents to avoid the chlorination step which is costly in terms of operation and energy expenditures.

D. SIMILARITY WITH OTHER TREATMENT SYSTEMS AND ADAPTATION OF HYDROPONIC SYSTEMS

The NFT principle differs in only one main aspect from typical hydroponic systems in commercial use. The nutrient solution is applied as a thin film flowing past the root. This feature provides nutrients and water supply to the plant by capillary action in the root mass while maintaining root aeration. At the minimal slopes, aeration limitations can result from pooling of nutrient solution in the root mat, especially if the surface is not smooth. The aeration problems can be solved by increasing either the slope or flow rates. Aeration can be improved at higher flow rates, but the same effects can be achieved with intermittent flow.

A simple comparison between the NFT and existing land application systems can be made to clarify the differences between them. Known application rates in land treatment systems and the flexibility of using various kinds of plants would indicate that the NFT may be able to process wastewater at higher rates, control and conserve nutrients and other pollutants as or more efficiently, and provide control over and access for monitoring all inputs and effluent constituents. Slow rate and overland flow land treatment systems are limited to application rates of 5 to 16 cm (2 to 16 inches) per day, with application to soil once every five to seven days to provide a resting period which enables oxygen to penetrate the soil surface (among other effects created by the "resting phase"). The eventual design of an NFT will most likely use daily application, with little or no resting period, and applications of greater than or equal to 40 centimeters of water per day.

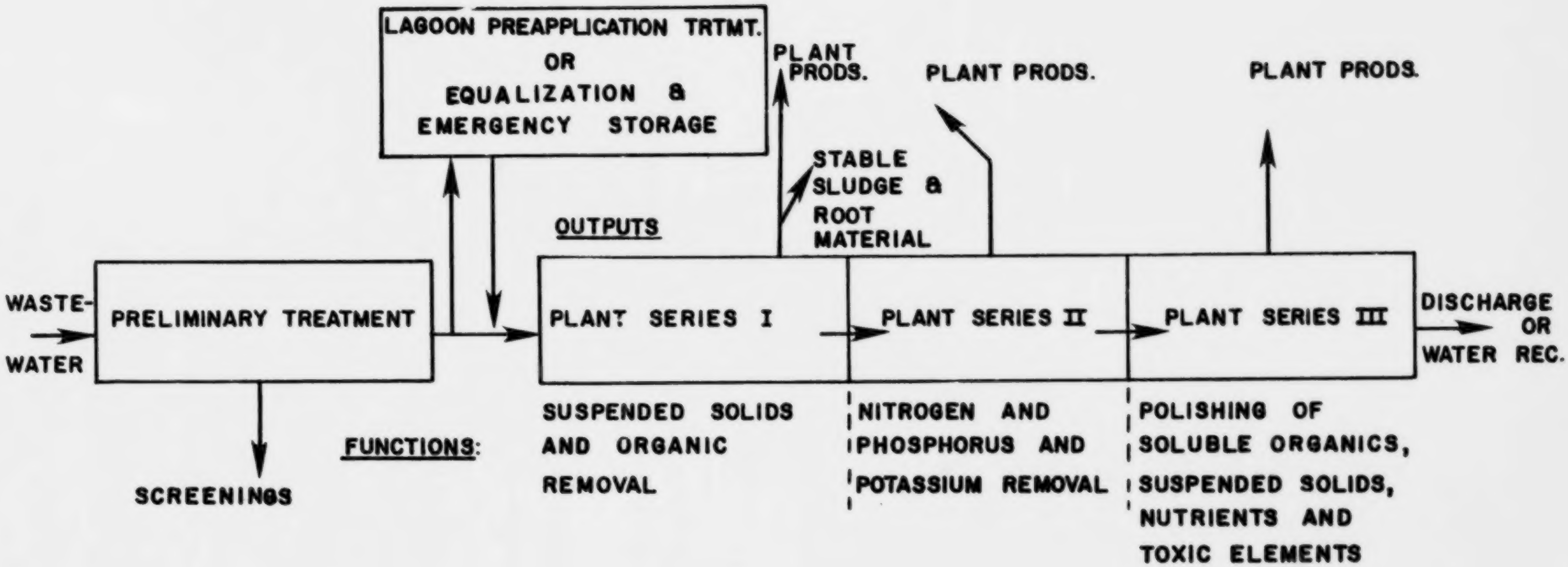

WASTE-
WATER
PRELIMINARY TREATMENT
SCREENINGS
LAGOON PREAPPLICATION TRTMT.
OR
EQUALIZATION &
EMERGENCY STORAGE
OUTPUTS
FUNCTIONS:
PLANT SERIES I
PLANT SERIES II
PLANT SERIES III
PLANT PRODS.
STABLE SLUDGE & ROOT MATERIAL
PLANT PRODS.
PLANT PRODS.
DISCHARGE OR WATER REC.
SUSPENDED SOLIDS AND ORGANIC REMOVAL
NITROGEN AND PHOSPHORUS AND POTASSIUM REMOVAL
POLISHING OF SOLUBLE ORGANICS, SUSPENDED SOLIDS, NUTRIENTS AND TOXIC ELEMENTS

Figure 1.2. Schematic diagram showing three-stage hypothesized NFT treatment system for domestic wastewater with functions for each stage and fate of all materials.

Finally, the NFT appears to have interesting economic potential. If it is assumed that the treatment area requirements will be less than 5 ha per 10,000 people, the capital cost of the structure will be between $2 million and $4 million; a capital cost comparable to conventional treatment systems. The production of valuable ornamental plants would result in an annual gross return on the order of $1 million to $2 million per year. An effort will be made to translate the system requirements into cost effectiveness to clarify the above implications.

E. LIMITATIONS TO THE NFT WASTEWATER TREATMENT

While the NFT has shown promise in this pilot study, several comments must be made regarding the practical limitations of the system. In order to operate on a year-round basis the system must be protected from low winter temperatures by a greenhouse cover. The cover is also required to recover evapotranspiration (ET) in summer, in addition to sufficient ventilation. Attempting to grow valuable plants requires the retention of a qualified grower as well as increased costs in terms of appropriate lighting and environmental conditions. While this study used only a medium to low strength domestic sewage, even this substrate may have contained phytotoxic substances which in larger concentrations or shock loadings could severely damage an NFT unit; for example, an ammonia spill once wiped out a small stand of cattails. Another limitation is the possibility of overloading the system with solids. While solids settle and are degraded in the root zone, too heavy an accumulation can be damaging to some plants, as was seen in one case with reed canary grass. One additional caution, rather than limitation, is that plants must be selected for appropriate roles in the NFT system; the characteristics and performance of a particular plant must be matched to the role which it is to play.

Large scale testing is required to document the costs of qualified manpower required to manage ornamentals and other plants that offer the possibility of substantial revenue generation. These must be contrasted to the operation and maintenance costs of small secondary treatment systems such as oxidation ditches or lagoons.

CHAPTER II

CONCLUSIONS

1. The nutrient film technique (NFT) has been shown to be a viable alternative for domestic sewage treatment in this three-year multidisciplinary effort. Pilot scale units up to 36 meters long have been operated continuously with domestic sewage at flow rates of up to 11,000 ℓ/d (3000 gpd) in New York and New Hampshire. Data presented here should be considered conservative since most experiments were conducted under "worst case" climate and temperature conditions. No attempt was made to control the plant environments during most of the testing.

2. The goal of this study was to examine the NFT concept as a possible wastewater/water supply treatment alternative. The results of this study show that, for the first time, most terrestrial plants can be considered as viable treatment organisms. The NFT process enables a photosynthetically-powered wastewater treatment facility to be considered for most treatment alternatives.

3. Application rates were examined which would enable the process to be competitive with existing processes. After steady state conditions were attained under a given loading rate, the loading rate was immediately increased. The main species that was examined in these tests was reed canary grass. Reed canary grass grown in the NFT system from seed and from transplanted sod resulted in the production of better than secondary effluent quality at an application of 10 cm/day under all applications throughout the year. Application rates at 20 cm/day were found to result in the destruction of the reed canary grass. Attempts to optimize multiple species systems that could exist in low dissolved oxygen environments eliminated the 20 cm/d limitation.

4. After the system was defined an optimized unit was constructed and tested on raw domestic sewage. This unit resulted in effluent quality significantly better than secondary quality with applications of 30 cm/day.

5. The area requirements and necessity for a greenhouse cover will vary depending on the location of the system. The following estimates can be made for an NFT secondary treatment system. The area needs appear to be approximately 2.7 hectares (6.6 acres) for a wastewater flow from a population of 10,000 people. This would be divided into two sections. The first section would be a roughing section of approximately

one hectare. It would be subdivided into relatively small sections so that the wastewater could be rapidly introduced, allowed to remain in a quiescent state for approximately one hour, and then removed slowly so that laminar flow conditions would occur. The second section would be a polishing and nutrient removal section of about two hectares. The capital investment of such a system appears to be attractive, and energy requirements would be low since only low head pumping would be required in such a system. Although a detailed economic analysis was not completed in this study, it appears that the capital investment would be less than conventional secondary treatment alternatives.

6. The application of the NFT for nutrient removal is subject to the limitations of all plant systems. Even with maximum growth rates the nutrient removal rates are relatively low in comparison to high rate nutrient manipulation processes such as microbial nitrification-denitrification. However, partial nutrient polishing could be achieved in NFT units of 10 ha/MGD or larger. These large greenhouse installations would be much larger than any other existing covered plant installations. However, the value of plant products may be high enough to justify use of the NFT as a nutrient recovery and/or water reclamation unit operation.

7. This study was able to define some of the general pollutant removal mechanisms. By accumulating large quantities of biomass in the form of fine roots, the possibility of removing pollutants is greatly enhanced. The solids entrapped in the roots provide the largest capability of this treatment system. Measurements of the solids within the roots indicated that over 1,000 gm/m^2 of entrapped solids was accumulated. These solids represent significant potential for manipulation of pollutant cycles. If, for example, this biological organic material can be utilized for pollutant removal, then the solids retention time becomes important. In such operations, reasonably high loading rates result in solids retention times of greater than 100 days. This indicates that the process could be stable and provide an efficient treatment system.

   Organic removals are limited by the level of aeration. The capillary mat of dense root systems may significantly increase aeration. The use of plants such as cattails that translocate air to their roots could also be a significant factor. Additional studies are needed in this area.

   The fine suspended solids were found to biocoagulate in the system, and high clarity effluent was achieved under high loading rates.

8. A major goal of this study was to manipulate the nitrogen cycle using both plants and microbial interactions via nitrification-denitrification. Nitrification was rarely observed during the study and produced only 2 or 3 mg/ℓ of nitrate-nitrogen under the lowest loading condition during the warmer time periods. This lack of

nitrification resulted in limited capability for control of the nitrogen cycle with the NFT.

9. Phosphorous removal appeared to be limited by the plant nutrition requirements. Due to the stress condition of most of the testing that occurred, phosphorous removal rates were low in the NFT system.

10. The relatively high temperature of domestic sewage is likely to provide enough heat to maintain plant cultures in the NFT in most areas of the U.S. where low cost solar greenhouses can be utilized. In some locations the greenhouse cover of the NFT system may be minimized due to this available energy.

11. The kinetics of pollutant removal were examined using several different approaches. Due to the large number of variables, no comprehensive model was established that would predict the process efficiency. The following rates indicate the range of observed nutrient and organic removals that were obtained in the system:

Parameter	Removal Rate kg/ha-d
BOD	44-166
TOC	26-97
COD	99-247
SS	17-164
N	2.8-12.7
P	0.4-1.8

12. Both heavy metal and organic toxic materials were examined in this system. Cadmium was added to the synthetic wastewater tested. Trace organics were added to the domestic sewage in the New Hampshire test facility. It is proposed that the removal mechanisms for the metals and the organics was the extensive root surface area and the large accumulated biomass. The following efficiencies were obtained for the given organics tested:

Toxic Organics Tested	Removal Efficiency Achieved
Chloroform	96
Tetrachlorethylene	95
Benzene	94
Toluene	97
Trichloroethylene	91
Xylene	94
Bromoform	98
M-Nitrotoluene	96
Diethylphthalate	72
PCB 1248	94

13. An attempt was made to define the relationship of hydraulic loading rates and hydraulic retention time within the root zone. Due to the large number of factors that affected the plants and the flow through the system, only general comments can be made.

14. The most promising empirical approach provided by the kinetic analysis of data indicated that the loading rate/effluent quality relationships would hold over a limited range for domestic sewage. These relationships will be of limited value in designing the NFT system for other wastewaters.

15. This study attempted to conduct parallel testing with actual domestic sewage and a synthetic sewage. Parallel comparison of these systems indicated that it was possible to simulate the domestic sewage systems with the synthetic wastewaters. Since the synthetic sewage contained soluble substrates only, it was not possible to simulate solids behavior or interactions with the synthetic sewage.

16. The water balance was established for a number of bench scale and pilot tests. Although in many circumstances the expected loss of water through evapotranspiration was equal to literature values of approximately 50,000 ℓ/ha-day, several test conditions resulted in water losses up to 100,000 ℓ/ha-day.

17. The energy and process requirements to recover evapotranspired water from the greenhouse were examined. Energy costs of ET recovery are extremely high and prohibit this alternative unless a low cost energy source is available.

18. Although reed canary grass was examined in the majority of tests in this study, a wide range of plants was cultured and propagated to examine their viability in the NFT system when applied to wastewater treatment. The following summarizes those plants that grew well and those that were less acceptable under adverse conditions:

Plants that flourished

Cattails
Bulrush
Strawflowers
Japanese millet
Roses
Napier grass
Marigolds
Wheat
Phragmites

Plants with marginal growth

Bristly sedge
Chrysanthemums
Carnations
Tomatoes
Comfrey
Reed canary grass
Soft rush
Cucumbers

19. The above list of plants includes some that have high monetary value. Reed canary grass, when grown under relatively low nutrient conditions, resulted in biomass with a total nitrogen content of 5 percent with most values greater than 4 percent. This indicates a total protein content of greater than 30 percent of the total dry weight in many cases and a plant that would have a significant animal food value. Plants with ornamental value such as shrubs, trees, and roses would represent plants with significant commercial value. Other plants that showed promise in this study were several food plants that would be useful for propagation purposes. Certain plants with a high value, such as berry plants, could be cultured in this system. The potential carry-over of toxic materials would be a concern with food products.

20. The growth of plants in sewage, where the organic and suspended solids loading rates are high, results in an optimum condition for inhibition of plant growth and pest invasions. The application of hearty plants such as cattails in the roughing sections of the NFT eliminated most of the plant pathogen problems that were observed; however, fungus invasions, insect attack on many of the plants, and other problems of greenhouse plant production were common. All the typical greenhouse production problems were controlled when advice from specialists was sought and implemented. The destruction of a total treatment system by pests or by contaminants in wastewater is a concern that needs careful evaluation prior to full scale implementation.

21. The technical and economic feasibility of the NFT as a treatment alternative was briefly examined in this study. It appears that the area requirements to achieve secondary quality effluent from either raw or primary settled domestic sewage would result in a cost competitive system without taking advantage of any of the reduced operation costs or the potential commercial benefits of biomass production. Solids flushing and removal alternatives would be required with the application of raw sewage. The estimates for tertiary treatment or water reclamation with the NFT indicate area requirements that may not be competitive with a conventional unit process unless the plant products have a commercial value. If plant management techniques are achieved that allow plant products to enter commercial markets, the use of the NFT as a water reclamation facility shows significant promise.

22. This study outlines a new approach to the use of plants as solar powered water and wastewater treatment devices.

CHAPTER III

RECOMMENDATIONS

This comprehensive feasibility study represents the first time that a wide variety of plants has been shown to be possible candidates for use in waste water and water supply treatment. The NFT process opens up a wide variety of applications of photosynthetically powered treatment processes. The results were intended to show the broad scope of applicability of plants to waste treatment. The experiments, however, were subject to strong limitations in terms of defining the fundamental interactions. In the complex plant solution systems it was difficult to understand how pollutants were removed and what happened to them in many parts of the NFT process. The following outlines topics that need further attention preceding the commercialization of the technology.

A. ADDITIONAL SPECIES SCREENING AND PARAMETRIC EVALUATION

While this work has identified many plant species that could grow well in NFT systems, the study did not match pollutant uptake characteristics with plant end uses. The interaction of the many variables in pollution control with potentially valuable plants will require a considerable screening effort to identify rapidly growing plants with useful products that can safely enter commercial markets. Considerable research needs to be done on this topic. In addition, experiments need to be conducted over the life cycle of plants to measure their useful life span in an NFT system.

B. POLLUTANT REMOVAL MECHANISMS

This study delineates the loading rates and some of the associated retention times that are required to remove pollutants in the NFT system. The primary missing knowledge is the location and fate of many of the pollutants. For example, the system has a potentially large capacity to entrap and use microbial solids in root systems since they accumulate over 1000 gm/m^2 and the solids retention time is greater than 100 days. The effectiveness of this microbial mass in pollutant control and methods of manipulating it must be determined. The impact of surface area and bacterial attachment in the NFT also remains to be defined. It is likely that the photosynthetically produced surface area is one of the most important parameters controlling pollutant removal. Also whether bacteria associate with or grow on these surfaces as attached films and their capability for pollutant control needs to be defined. Some form of solids removal must be incorporated so that rapid flushing can be used to remove bioflocculated solids on an intermittent basis.

C. AERATION DUE TO CAPILLARY MAT IN REED-TYPE PLANTS

There is some information that suggests that the oxygen supplied by the capillary mat in the NFT in hollow plants, such as the bulrushes, is a significant factor in solids control. Biocoagulation of fine suspended solids in this study was observed under most conditions. This resulted in the production of a highly clarified effluent. The factors that control this may contribute to a useful method for solids control.

D. LOWER NUTRIENT EFFECTS ON YIELD

Before the NFT can be applied as a nutrient removal system, methods of defining plant performance with limited nutrients must be known. Since plant production under limited nutrient conditions is not the goal of most agricultural operations, relatively little information exists. There are, however, certain management approaches that would enable nutrients to be removed from the wastewater while limiting growth substances are applied directly to the plant leaves. Management techniques to provide a high quality effluent from the NFT system should be examined.

E. ET RECOVERY

The large energy and capital investments for evapotranspiration recovery in greenhouses is a strong negative factor in the production of ultrapure water from the NFT system. However, some large measured ET values, exceeding by many times the literature values reported for normal plant production, suggest that the capillary mat in the NFT can be managed to increase the water recovery from NFT systems.

F. DRINKING WATER AND POLISHING APPLICATIONS

Numerous water supplies are contaminated with nitrates and other nutrients that would provide a nutrient base for an NFT system. Plants should be tested for drinking water and other polishing-type applications. This research should include examination of organic exudates that are produced in the roots and other by-products that could be observed in clean water applications.

G. NITROGEN CYCLE MANIPULATION WITH THE NFT

One of the most important aspects of wastewater treatment is control of the nitrogen cycle. The lack of nitrification in the long-term testing in this project was one of the surprising outcomes. Methods of achieving nitrification with the NFT should be examined.

H. SCALE-UP OF OPTIMUM NFT SYSTEMS

The positive nature of this study indicates that the technology may play a wide role in pollution control. Efforts should be made to test the NFT at larger scale under longer term operations. Until example facilities are available for review by the pollution control engineers, this innovative technology is likely to be largely ignored.

CHAPTER IV

BACKGROUND AND LITERATURE REVIEW

The use of plants in pollution control systems is an old concept, but few definitive studies have been conducted to identify and quantify the mechanisms responsible for pollutant removal. Even less information is available for the application of the unique hydroponic plant growth system referred to as the nutrient film technique (NFT) to sewage treatment. To obtain background information on the new application of the NFT it is necessary to review a wide range of literature and topics.

More than 10,000 plant and soil waste treatment systems are presently in use in central facilities, and more than 60 million people depend on aspects of the plant-soil complex to purify septic tank effluents (Jewell and Seabrook, 1979). Total land area requirements for conventional aquatic or land treatment systems range from several hectares to over 100 ha to process sewage generated from 10,000 people (see Table 4.1). In order to be a viable alternative, the NFT systems must offer better pollution control and/or cost advantages. Clearly, this is a formidable challenge since the NFT system will be a more complex plant system requiring a greenhouse cover in northern climates. In order to make such systems cost effective it will be necessary to reduce the area requirements and/or increase the value of the plant by-products.

Background literature was drawn from seven distinct subject areas:

1. commercial crop production in traditional hydroponic (soilless culture) systems;
2. development of the Nutrient Film Technique (NFT) as a commercial alternative for growers including:
   - •NFT hardware development,
   - •Plant culturing and nutrient experience with various crops in NFT, and
   - •NFT spin-offs such as vertical growth tubes and adaptations for root crops;
3. biological habitat and life-cycle studies of emergent aquatic plants;
4. aquaculture for waste treatment, including natural and man-made marshes, wetlands, ponds, and other systems;

TABLE 4.1. STATE OF THE ART CHARACTERISTICS OF AQUATIC SYSTEMS AND LAND APPLICATION SYSTEMS USED FOR DOMESTIC SEWAGE TREATMENT (from Reed, Bastian and Jewell, 1981 and EPA 1981)

Kind of Treatment System	Effluent Quality Achieved	Pre-treatment Required	Area Required ha/10,000 people or ha/3785 m^3 flow-d	Comments
I. Aquatic Systems				
A. Wetlands (Artificial or Natural)	Secondary+	Primary	10 to 30	Significant potential: economics and design need clarification.
B. Aquatic Plant Systems	Secondary	Primary	7+	Most information limited to water hyacinths, a warm climate nuisance plant.
	Polishing Secondary	Secondary	2.5	
	Upgrading Secondary to Tertiary	Secondary	5.4	
II. Land Applications				
A. Slow Rate	Drinking water	None	23 to 280	Hundreds of systems in use.
B. Overland Flow	Secondary +	Lagoons	6.5 to 44	Recent design criteria make them a useful alternative.
C. Rapid Infiltration	Tertiary	None to Secondary	3 to 23	Often limited due to availability of soils.

5. land application of wastewater by overland flow or slow-rate irrigation methods;

6. wastewater and water treatment in traditional hydroponic systems; and

7. conventional unit process wastewater treatment.

The NFT is a relatively new technology which has gained widespread acceptance by commercial plant growers only in recent years. The basic NFT configuration depends on the wastewater characteristics and the type of environment in which plants would be expected to function. Treatability studies in conventional systems yield parameters such as retention time needed for desired levels of treatment. Plant selection is accomplished in part by matching environmental tolerances of various plants with the conditions assumed or known to exist in an NFT wastewater treatment system. Such data have been compiled for many species, including wetland plants. The hypothesized NFT system assumes a "unit process" type of system in which well-adapted wetland species will occupy the initial units. These would be loaded with relatively large applications and act as biological filters and settling units, providing efficient roughing treatment to secondary quality levels. This effluent should provide substrate for growth of high value crops in lower rate NFT units of the type investigated to date in this research. In this way, there should be minimum compromise necessary between plant value and hardiness under adverse conditions. The polishing phase of this two-part system should be able to take advantage of the NFT's reported ability to serve as a medium for growth of almost any plant species (Schippers, 1977, 1979).

This review will concentrate on development of the NFT, plant culturing experience in the NFT, and wastewater treatment using any hydroponic system. The broader areas of hydroponics development, aquatic plants, aquaculture, land application of wastewater, and conventional wastewater treatment will be treated only as they relate specifically to NFT wastewater treatment. Aquatic plant physiology and morphology are discussed in some detail to illustrate the potential applications of the NFT system.

A. HYDROPONICS

Development of the general field of soilless plant culture systems, of which NFT is an outgrowth, goes back many years and encompasses many variations. No general review of hydroponics literature is attempted here. Hyppio (1974) provides a short, selected list of publications on hydroponics which includes entries from 1939 onward. Sholto-Douglas (1976) describes "nutrient flow" techniques bearing much similarity to NFT which have been in use in India since 1947. In the original version, plants were placed in holes in bamboo stems, through which nutrient solution flowed. Later, hoses and polyethylene sheeting were used. The Hygro-flo tube system, reported by LeSieur and Brungard (1977), is a process developed in the U.S. independently of NFT; but it shares some of the attributes of NFT.

The nutrient film cultural method was first developed as a research technique in 1966, but it was Alan J. Cooper who first recognized the commercial potential of the principle. Cooper's original research on the commercialization of the Nutrient Film Technique (NFT) was conducted at the Glasshouse Crops Research Institute (GCRI), Littlehampton, Sussex (Cooper, 1976). It was first introduced to the public by the group in 1969-70. Cooper was involved in early work with General Electric on the concepts discussed in this report. Additional university research has been conducted in the United States by Vinzant (1978) and Schippers (1979). Large-scale commercial development of the system was accomplished by the General Electric Company in Syracuse, New York. Many firms are active in the supply of equipment for NFT crop production, both in this country and in Europe.

Cooper (1976) provided a booklet of reprints of his original articles in The Grower, a weekly English journal for the horticultural industry. The first of these articles appeared in May, 1973, in which growth experiments with tomatoes were conducted. No large-scale NFT trials had been attempted at that time.

The NFT principle differs in only one main aspect from typical hydroponic systems in commercial use. The nutrient solution is applied in a thin film of liquid that flows through and over the root mass. This feature allows for nutrient and water supply to the plant by capillary action in the root mass while maintaining good root aeration. Plastic tubing or gullies (hydrocanals) make a desirable, impermeable, and chemically non-reactive surface for containing the gravity-fed nutrient solution. Because of the hydrophobic nature of most plastics, a capillary mat may be used to disperse the solution across the width of the gully. Rounded bottom gullies have been used but tend both to limit root growth and to result in more pooling of solution. Raised sidewalls and tops have been added to the gullies to retard evaporative loss and to provide some mechanical support. In turn, a high humidity level is maintained around the roots. The top surface of the gullies are variously black to prevent light transmission and white or aluminum to prevent nutrient temperature buildup. This plant production concept is now popularized and can be purchased from several seed and hardware companies for small home applications. This home scale application emphasizes the ease with which plants can be produced in the NFT system.

Schippers (1977a and 1977b) traced NFT development in an annotated bibliography which provided a concise summary of design changes, commercial applications, advantages and problems associated with the NFT, and the formulation and testing of nutrient solutions. Major advantages cited are the ease of plant handling, lack of water loss due to drainage, elimination of soil salinity and disease problems, quick visual inspection of the system and the whole plant, and energy savings due to heating of nutrient solution, resulting in lower greenhouse heat demand. Recommendations on nutrient formulations at first were very specific for each crop. However, experience showed that standard formulations could be used equally well on a variety of crops. This is a strong point in support of the use of NFT for wastewater treatment. Perhaps more incentive to apply the technology to wastewater treatment arose when plants were shown to thrive in low concentration nutrient solutions, contrary to what was believed originally.

Lauder (1976) demonstrated the use of timber-framed, plastic-lined gullies 0.91 meter (one yard) wide, for NFT production of grasses at GCRI. This basic design was adapted for use in this project, without the absorbent liners used in the GCRI units.

Potential problems discussed in Schippers' review include pooling of nutrients in uneven gully floors, deleterious effects of high ammonia nitrogen concentrations (limits not defined), "collar burn"--a condition arising from crystallization of salts, and perhaps most troublesome, root death. Darkening and withering of roots are mentioned in several articles, and are attributed to various causes, including oxygen deficiency and microbial infestation, particularly fungal blights. See Chapter VI for examples of root death in some Cornell test species.

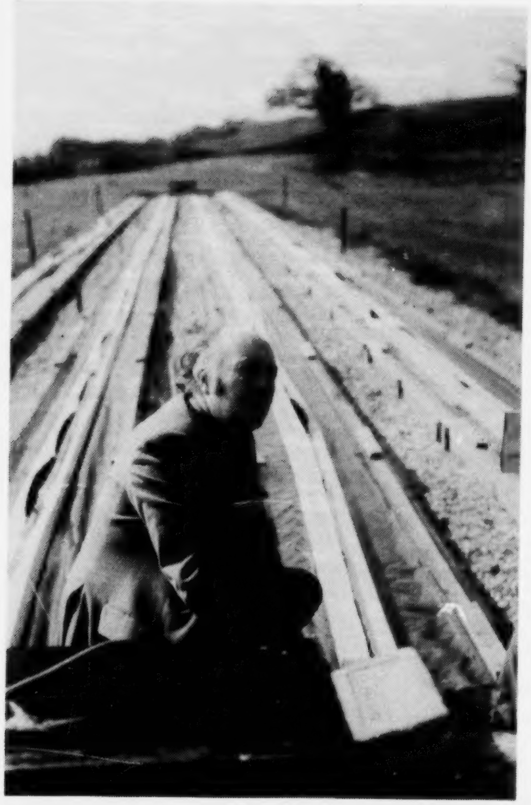
One major difference in NFT development between Great Britain and the U.S. is that the English growers are encouraged to buy whole systems from commercial suppliers, while in this country the emphasis is on their building the systems, following guidance from the researchers. Schippers (1977) provides a manual for growers on constructing and operating NFT systems. This information is updated in Schippers (1979) which presents a historical review and summary of three years' experience at the Long Island Horticultural Research Laboratory with various crops.

B. WASTEWATER AND WATER TREATMENT IN HYDROPONIC SYSTEMS

The authors are aware of only one other group studying the application of the NFT to wastewater treatment. The Waste Recycling Program of the Plymouth Portsmouth Polytechnic has been conducting a broad scope waste recovery research program at a large sewage facility in England since mid-1977 (Stead 1977, Stead 1978, Stead and Rome 1979, Anonymous 1982). One component of this study was the application of reverse osmosis for recovery of high quality water. The concentrated permeate from this unit process was used as a feed solution to the NFT. Comprehensive experiments showed the potential for production of a wide variety of food crops. Figure 4.1 shows some of the facilities in use by the Plymouth research group. The main focus of this activity has been on cultural aspects and the production of useful plant matter. These studies are continuing.

A few studies have been reported which involve hydroponics in some form of wastewater treatment or effluent polishing. Four separate computer literature searches (including the Aqualine system at the Water Research Center, Stevenage, England) were conducted. Of the twenty-two possible studies dealing with aquaculture, aquatic plants or hydroponics in sewage or wastewater treatment, the NFT was not mentioned.

Lewis *et al*. (1978) illustrated the use of hydroponic tank-grown tomatoes as a nutrient scrubbing unit of a recirculating-water system for fish production. The purpose of the study was to grow fish and tomatoes rather than treating wastewater; thus the authors' primary concern was to maintain a low ammonia concentration and provide a method to remove nitrate from the system. Channel catfish were grown in three 870-liter tanks with mechanical



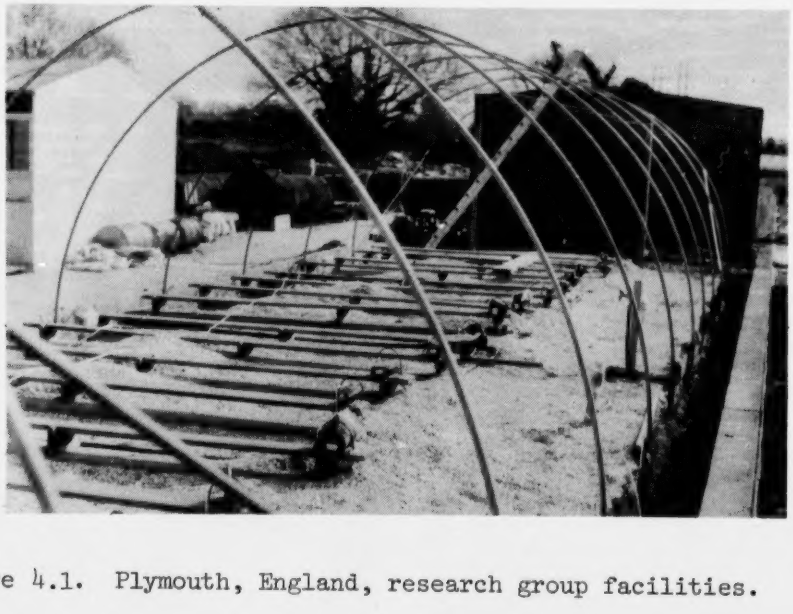


Figure 4.1. Plymouth, England, research group facilities.

aeration and automatic daily feeding. Effluent from the tanks passed through biofilters (rotating biological contactors, or RBC's) for treatment of organics and conversion of nitrogen and phosphorus to nitrates and phosphates. These were assimilated by tomato plants as clarified RBC effluent passed through the hydroponic system. The system worked well in preventing NH_3, NO_3^- and PO_4^{-3} buildup in the fish culture tanks, and tomato yields were approximately twice that of field trials on the same varieties. Removals of NO_3^--N and PO_4^{-3}-P averaged 14.3 and 14.8 percent, respectively, on a concentration basis, not adjusted for evapotranspiration losses. Considering that nitrate concentrations were usually fairly low (6 to 10 mg/ℓ), the authors concluded that this system showed promise of being able to meet nitrogen standards for fish culture when used in a single pass (treat and discharge) mode. Ammonia nitrogen did not exceed 1 mg/ℓ. Such a system without biofilters was reported by Sneed et al. (1975), who examined the production of several plants in catfish holding tank effluent.

Chinese water chestnut was grown on floating vermiculite rafts in catfish tanks in South Carolina by Loyacano and Grosvenor (1973). Three treatments of pools stocked with catfish were replicated in their study: open pools, pools with rafts only, and pools with water chestnuts growing in the rafts. Both the raft and water chestnut treatments resulted in increased fish survival and more efficient feed conversion. Water chestnut yields amounted to a rate of 3176 kg/ha of pool surface over a seven-month period. No water quality data were given, but this study also demonstrated the feasibility of hydroponic plant production on this type of wastewater. Harmon (1980) conducted tests to determine whether effluent water produced from an intensive fish farming operation could be treated with the NFT. The results of three small scale experiments were positive although inconclusive.

Sias and Neven (1973) described a hydroponic gardening system in which beans, radishes, and tomatoes were grown in secondary sewage effluent from the City of Melbourne, Florida. A major emphasis was on comparison of irradiated versus chlorinated effluents ($\geq$ 2 ppm free chlorine residual), and plant growth was also compared in sewage versus nutrient solutions. They generally found much better growth in irradiated or untreated wastewater effluent than in chlorinated effluent or in chlorinated, irradiated, or untreated nutrient solutions. Nitrate, ammonium and phosphate levels were monitored in two hydroponic units, one planted with beans and radishes and the other without plants. Results were not reported, however, because the small size of the units did not provide enough plants to obtain measurable uptakes. The units consisted of containers of perlite, 15 cm (six inches) deep and 107 cm (42 inches) in diameter. Fifty-seven liters (15 gallons) of sewage or nutrient solution were used every three days, which translates to a loading of only two centimeters (0.8 inches) per day over the available tank surface area. Wastewater characteristics were not addressed except for some discussion of coliform counts in the various experiments.

Wastewater hydroponics formed one part of an overall study of nutrient recycling in hydroponic and aquacultural systems at UCLA (Gordon, 1977; Wallace et al., 1978). Hydroponics was considered only in conjunction with conventional wastewater treatment. Severe iron (Fe) deficiency occurred in early tests even when sewage was renewed twice daily. In later greenhouse studies, Fe supplements were given in the form of insoluble iron applications to the roots before transplanting to the tanks, or Fe chelate added directly to the sewage effluent. Conclusions drawn to date are that the system provided for commercial-scale production of cucumbers, tomatoes, lettuce, and chrysanthemums, with significant heavy metal reductions and variable N and P reductions in the wastewater.

The solar aquacell process (Serfling and Alsten, 1979) has been demonstrated in at least three California communities in pilot scale since 1976. The process has been the subject of many articles in various journals and proceedings since its inception in 1972 as an intensive aquaculture system for raising freshwater fish and shrimp. It was noted in working with this system that water quality was maintained at a high level even though the fish waste and the commercial fish feed, cow manure, and chicken manure used as nutrient sources produced an organic and nutrient loading very similar to that of domestic sewage. Of the major wastewater constituents, only phosphates were significantly lower in the fish production system. Results from two California communities, Solana (5700 ℓ/day) and Cardiff (11,400-22,700 ℓ/day), indicated that primary effluent averaging about 90 mg BOD_5/ℓ and 170 mg BOD_5/ℓ, respectively, could be treated to BOD_5 levels of about 10 mg/ℓ or less in four days' retention time in the aquacells. At the same time, suspended solids were reduced from about 100 mg/ℓ to well below 10 mg/ℓ. Good nitrification was achieved, but effluent nitrate levels would not meet drinking water standards. Phosphate levels were highly variable. Estimates based on limited data showed an average removal rate of 0.5-1.0 mg/ℓ total phosphate per day.

It should be pointed out that the higher plant component of the solar aquacell process consists of floating plants (duckweed and water hyacinth) which contribute little direct benefit to wastewater treatment. The plants provide shade to limit algal growth, some uptake of nutrients, heavy metals and other toxic substances, and provide filtration and microbial attachment sites in their roots. Water hyacinth and duckweed have conferred these benefits on wastewater lagoon systems in other studies (for example, Wolverton and McDonald, 1979). The aquacell system employs inert plastic mesh webbing strips anchored to the pond floor to provide additional surface for microbial attachment. In addition, the ponds are aerated and contained within a double-wall polyethylene greenhouse. These last three items provide the bulk of the aquacell's treatment performance improvement over conventional lagoons. Also, the aquacells are always used in conjunction with some form of primary treatment, either settling basins or anaerobic lagoons. The authors state that secondary treatment levels can be achieved within two days' HRT without floating plants in the system, according to their operational experience. So, although the system contains some elements of hydroponics, it is not a true hydroponic treatment system as described elsewhere in this report. It is rather a combination of lagoon and conventional treatment technology, designed to provide shorter retention times and more consistent treatment in situations where lagoons would be appropriate. Hydraulic retention times on the order of days do not compare favorably with HRT demonstrated for the NFT system in this study. The largest solar aquacell system to date, 1300 m^3/d (0.343 MGD), in Hercules, California, has been delayed in achieving full operation due to an undersized primary treatment unit (Parkinson, 1981).

C. PLANT PHYSIOLOGY AND MORPHOLOGY IMPLICATIONS

Effective and economical sewage treatment in the NFT system is influenced by plant survival, nutrient uptake, growth rates, and yield. Although a large amount of information exists on aquatic plant growth, key questions remain to be addressed: what differences exist between nutrient solution and sewage behavior in the NFT; what are the physiological implications of the differences to plant survival and growth; and finally, which plants are best able to thrive in the sewage environment. In this chapter literature pertinent to these questions is reviewed.

As the NFT system must remove several fractions of wastewater contaminants (dissolved and particulate organics and inorganics), plant characteristics other than survival are important. Particulates are removed as the water velocity slows; since the density of planting, root mass, and shoot diameter affect the water velocity. Because dissolved inorganics can be removed by bacterial and plant uptake, the plant growth rate, biomass production and the root surface area available for bacterial attachment are important factors. Table 4.2 summarizes the plant characteristics critical for successful operation of some removal mechanisms in NFT sewage treatment. This chapter also reviews the occurrence of plant characteristics among taxonomic groupings and the influence on these characteristics of growth in sewage film. Similarly, Table 6.17 (Chapter VI) shows those characteristics considered desirable in an NFT system as a whole.

TABLE 4.2. PLANT CHARACTERISTICS IMPORTANT FOR WASTEWATER TREATMENT MECHANISMS IN AN NFT SYSTEM

	Type Pollutant Removed		
Plant Characteristic	Particulate	Dissolved Inorganic	Dissolved Organic
Biomass	+ *	+	0
Growth Rate	0	+	0
Density of planting	+	+	+
Shoot diameter	+	0	+
Root/shoot ratio	+	+	+
Root surface area	+	+	+
Root volume	+	+	0
Root exudation	0	-	-

*(+ = positive effects; 0 = no effect; - = negative effect)

C.1 Redox Potential and the Effect of Sewage Film on the Plant Root Environment

The nutrient film technique for hydroponic plant culture is successful because the trickle of solution supplies plant roots with nutrients and maintains an adequate exchange of dissolved gases. When sewage is used as the nutrient film, the nutrient supply and gas exchange may be depressed due to direct and indirect effects of the reduced state of chemicals in the sewage film. It is likely that depressed dissolved oxygen concentrations will have the greatest effect on plant species that can survive and grow in the NFT system.

The reduced chemicals act as a sink for dissolved oxygen in the sewage film from both chemical oxidation and biochemical utilization of the reduced substrates. Microbial utilization of the substrates will raise the concentration of carbon dioxide in the sewage film. In addition, the bacterial and fungal populations developing on the plant root masses will create a physical barrier to gas exchange between the roots and the sewage film.

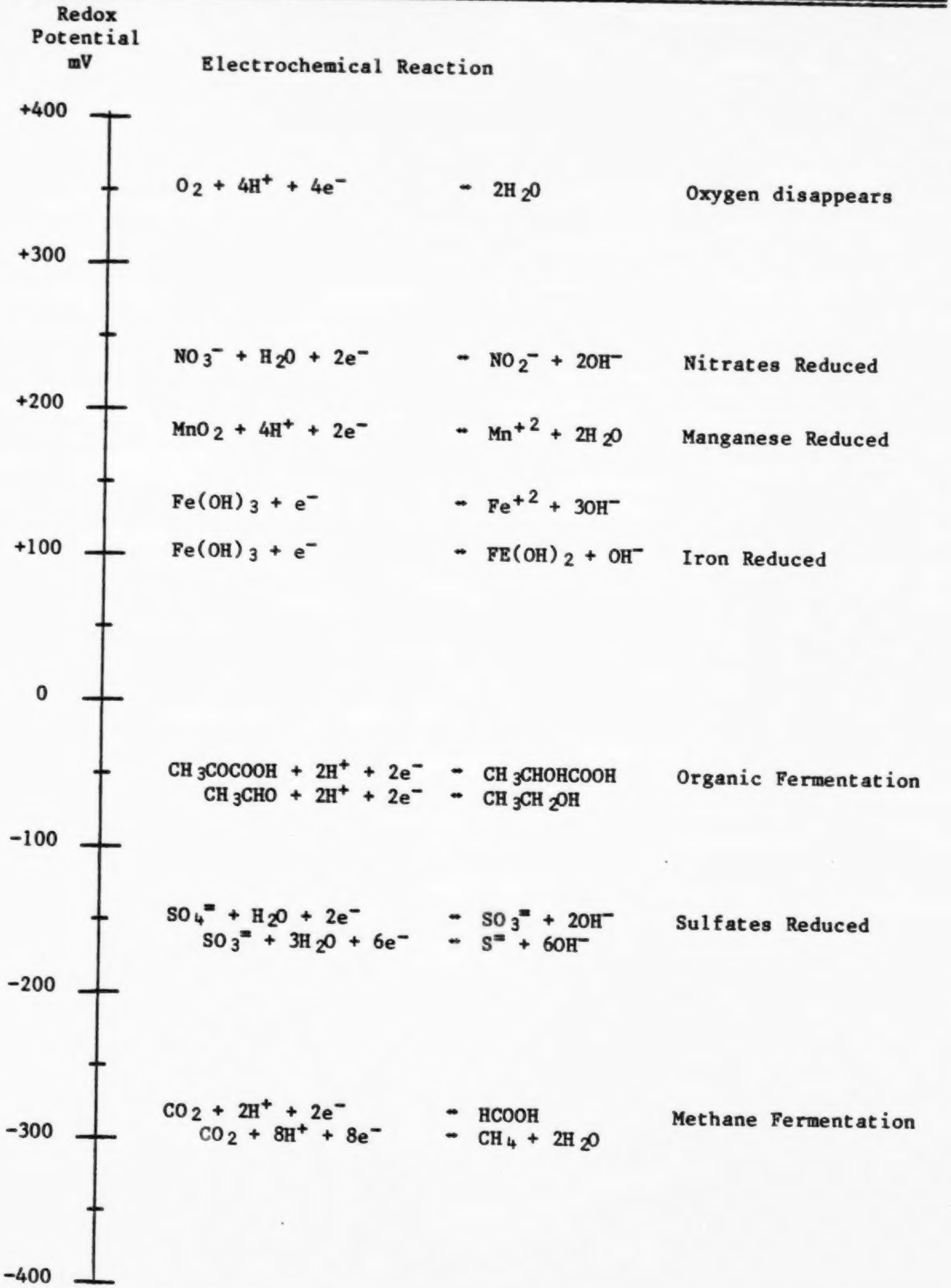
As oxygen is depleted in the sewage film, the oxidation state, solubility, and consequent availability of mineral nutrients will change. Redox potential, a measure of electrochemical potential or electron availability, may be used to indicate the degree of oxidation or reduction in the root zone. The influence of redox potential on mineral nutrient availability and plant growth has been reviewed by Gambrell and Patrick (1978) and Ponnamperuma (1972) for submerged soils. Although the sewage film is quite different from soil and soil water in levels of minerals and exchange sites, chemical behavior in both systems can be expected to be similar. The chemical transformations that affect nutrient availability and toxin production can be predicted from the redox potential of the system.

Figure 4.2 summarizes the approximate critical threshold redox potential values for some nutrients important to plant growth. When molecular oxygen is present in a solution, the redox potential usually will range from +400 to +700 mV (Gambrell and Patrick, 1978). As oxygen is depleted by chemical and microbiological activity, nitrate becomes reduced. Nitrate can be used by many organisms as an electron acceptor; the redox potential will stabilize between +200 and +400 mV until nitrate is depleted.

Manganic compounds (Mn^{+4}) reduce to the more soluble manganous (Mn^{+2}) at an oxidation level comparable to that of nitrate (200 mV). There are, however, fewer organisms which are able to use manganic compounds directly as electron acceptors.

The next system to be reduced is the ferric-ferrous compounds. Iron is particularly important to plants. $Fe(OH)_3$ will be reduced to the highly soluble Fe^{+2} at around +120 mV. Ponnamperuma (1972) considers that this reduction is probably not biologically mediated and therefore not important in flooded soils. However, Bohn *et al*. (1979) stated that iron redox reactions occur at appreciable rates in soils without enzymatic catalysis, and thus iron reduction may occur.

FIGURE 4.2. APPROXIMATE CRITICAL THRESHOLDS FOR STABILITY OF REDOX SYSTEMS



$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$ Oxygen disappears

$NO_3^- + H_2O + 2e^- \rightarrow NO_2^- + 2OH^-$ Nitrates Reduced

$MnO_2 + 4H^+ + 2e^- \rightarrow Mn^{+2} + 2H_2O$ Manganese Reduced

$Fe(OH)_3 + e^- \rightarrow Fe^{+2} + 3OH^-$

$Fe(OH)_3 + e^- \rightarrow FE(OH)_2 + OH^-$ Iron Reduced

$CH_3COCOOH + 2H^+ + 2e^- \rightarrow CH_3CHOHCOOH$ Organic Fermentation

$CH_3CHO + 2H^+ + 2e^- \rightarrow CH_3CH_2OH$

$SO_4^= + H_2O + 2e^- \rightarrow SO_3^= + 2OH^-$ Sulfates Reduced

$SO_3^= + 3H_2O + 6e^- \rightarrow S^= + 6OH^-$

$CO_2 + 2H^+ + 2e^- \rightarrow HCOOH$ Methane Fermentation

$CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O$

Intermediate dissimilation products of organic matter (fermentation) form the next oxidation-reduction couples. Pyruvate-lactic acid is one example cited in Stumm and Morgan (1970), who point out that organic carbon compounds (with the exception of methane) are unstable over the entire range of redox potential, but anaerobic conditions are more favorable to their preservation than aerobic conditions.

Sulfate reduction will be initiated when the redox potential falls to approximately -150 mV. Hydrogen sulfide (H_2S) results, and may escape from the sewage film as a gas. Ponnamperuma (1972) reports that proteins, fatty acids, amines, and diamines will be degraded at this redox level as well.

Methane fermentation can occur as the redox potential falls between -250 and -300 mV. Gambrell and Patrick (1978) conclude that most of the sulfate must be reduced to sulfide before methane production begins. However, most of the other redox systems can overlap; for example, nitrate may be reduced in the presence of oxygen, and manganese may be reduced in the presence of nitrate but not in the presence of oxygen.

In addition to the changes in availability of plant nutrients, a reduced root zone has important implications for the presence of phytotoxins. The end products and by-products of anaerobic metabolism by root zone organisms can be toxic to plants. Jackson (1980) considers incompletely oxidized carbon compounds produced from anaerobic metabolism to be phytotoxins. Examples of such compounds are ethanol, acetaldehyde, and the aliphatic acids: acetic, butyric, and propionic acid.

The sewage film thus induces conditions of low dissolved oxygen, heightened carbon dioxide concentrations, changes in nutrient availability, and presence of phytotoxic substances relative to aerobic soils and non-carbonaceous nutrient film solutions.

C.2 Physiological Implications of Growth in Sewage Film

C.2.a Plant Response to Anaerobiosis--

The effects on the whole plant of an anaerobic or reduced root zone have been documented by plant physiologists interested in the impacts of flooding. Much of this literature has been reviewed by Drew and Lynch (1980); they summarize the general effects of anaerobiosis as: slowing of leaf and shoot extension, chlorosis, epinasty and abscission of lower leaves, wilt, stunting and degeneration of roots, formation of adventitious roots at the base of the stem, and inhibition of transport of essential nutrients, minerals, etc., from the root to the shoot. Research has focused on the cause of the plant symptoms (oxygen depletion, carbon dioxide accumulation, or phytotoxins) and the mechanism of induction of the response (hormonal disruption, nutrient deficiencies, or low energy from glycolysis).

Early studies demonstrated that the rate of mineral accumulation in roots is directly related to the oxygen deficiency (Steward and Berry, 1936). A series of experiments by Hopkins *et al.* (1950) tested the effect of three concentrations of dissolved oxygen (0.2, 0.9 and 2.2 mg/ℓ) on root growth and whole plant response of tobacco, soybeans, and tomatoes. At the lowest concentration of dissolved oxygen, root extension stopped; at 0.9 and 2.2 mg/ℓ adventitious roots were stimulated. The growth and color (intensity of green) of the whole plants were proportional to the oxygen concentration in the solution. Most of the responses of the plant were proportional to the log partial pressure of oxygen in the nutrient solution. Elemental composition of the plants in these experiments indicated that amounts of many major nutrients (potassium, calcium, magnesium, and phosphorus) closely paralleled growth response.

The effects of low oxygen on the morphology and size of roots was tested by Geisler (1965), who grew peas in aerated and non-aerated hydroponic culture. Roots in the non-aerated system (dissolved oxygen 3-4 mg/ℓ) showed less growth and fewer primary and secondary lateral roots. The lateral roots were more closely spaced, and the amount of branching increased in the non-aerated system. A conflicting opinion was voiced by deWit (1978) who concluded that roots in non-aerated culture will be more porous, straighter, thicker, and more numerous, that root hair growth will be suppressed, and that the absorption surface will be larger.

Work by Chang and Loomis (1945) tested the effects of carbon dioxide on mineral and water absorption by plants grown hydroponically. Solution vessels were purged of oxygen by carbon dioxide or nitrogen gas, and the absorption of water, nitrogen, phosphorus, calcium, magnesium, and potassium was measured. Absorption of all five minerals and of water were reduced by the CO_2 treatment, and not by N_2. The implication was that the effects of the CO_2 treatment were due to the gas and not to the exclusion of oxygen. The reduction in Ca and Mg absorption was proportional to the reduction of water uptake, while the relative absorption of N and P were half that of water. K was released from roots in two of four experiments. The implication of these results is that Ca and Mg accumulation is least dependent on metabolic activities, that K metabolism is very sensitive to the root environment, and that N and P require an active transport.

The role of CO_2 as an indicator of flooding damage was confirmed by Kramer and Jackson (1955) in a study of tobacco plants. Wilting could be induced by displacing O_2 with CO_2 in soil column experiments; the wilting response was much more severe with CO_2 than with N_2. A review of these and other experimets concluded that a partial pressure of CO_2 (pCO_2) of 5 to 10% in the culture solution would inhibit nutrient and water uptake and retard growth of roots and shoots (Ponnamperuma, 1972).

Attempts have been made to separate the effects of low oxygen, elevated CO_2 and phytotoxins on the plant response to anaerobiosis in the root zone. Sanderson and Armstrong (1980) tested the separate effects of anoxia, volatile fatty acids, and ethanol on conifer roots, and concluded that anoxia was the primary cause of root death. Trought and Drew (1980) conducted experiments to monitor and correlate external changes in the root zone and internal changes in the whole plant. The rapid changes observed in the whole plant (decrease in accumulation of shoot dry matter, inhibition of root growth, decrease in transpiration rate) were apparently in response to a rapid decline in O_2 concentration. CO_2 and ethylene accumulated much more slowly.

Despite some experimental evidence that CO_2 levels are critical, the current consensus seems to be that lack of oxygen is the primary factor in waterlogging damage to plants. Experiments that tested the minimal partial pressure of dissolved oxygen that still allowed root growth and function are equivocal, due to the difficulty in actually measuring the oxygen pressure experienced by the root. Certain experiments indicate that dissolved oxygen tensions as low as 0.1 mg/ℓ at the porous cortex may be sufficient for ion uptake (Drew and Lynch, 1980).

Hormonal control in the plant is strongly implicated as the mechanism responsible for the visible symptoms of damage from low dissolved oxygen in the root zone (see Russell, 1977, for a review of plant hormones). Poor aeration in the root zone inhibits the synthesis and translocation of cytokinin and giberellins. These plant hormones inhibit the symptoms of premature senescence (chlorosis and abscission) that are provoked by an internal redistribution of the mobile nutrients (N,P,K) to younger leaves. Reduction in leaf extension and shoot elongation has also been associated with interference in the synthesis and transport of cytokinins and giberellins. Adventitious rooting, the emergence of porous roots from the base of the stem, has been correlated with inhibition of giberellin synthesis and transport in the low oxygen root environment (Reid and Crozier, 1971).

Accumulation of abscisic acid in the leaves of flooded plants may contribute to stomatal closure, which would account for the reported decreases in transpiration rate (Drew and Sisworo, 1979). This plant hormone is also associated with early leaf senescence and inhibition of shoot growth.

Ethylene levels rise in the aerial portions and in the roots of flooded plants. Chlorosis of leaves has been associated with increases of ethylene in plant shoots. Kawase (1981) has determined that ethylene trapped in root cells will induce cellulase activity, which causes cell death and disintegration. Lacunae (open channels in the root cortex) are formed when the cells die. This response may be adaptive for the flooded plant, as lacunae have been implicated as passageways for oxygen flux from the shoots to the roots. Lacunae are discussed in greater detail in section C.3.a.

The changes in plant hormone levels are due to the failure of roots to provide nutrients; the failure of the roots to provide nutrient ions is due to lack of oxygen (Drew and Sisworo, 1979). Thus, although hormonal disruption provokes the symptoms of waterlogging damage, the mechanism must be traced back to the lack of oxygen.

A deficiency of oxygen will force cells to metabolize anaerobically. Metabolism of carbohydrates without oxygen as a final electron acceptor (fermentation, glycolysis) in the root cells of flooded plants has important implications: the yield of energy to the cell is reduced, and toxic end products or by-products of fermentation may accumulate. Vartapetian (1978) considers the low energy yield to be of fundamental importance in the disruption of nutrient uptake and assimilation. Ethanol, an end product of glycolysis, kills cells by solubilizing lipids, inactivating mitochondrial enzymes, and causing cell leakage (Crawford, 1978).

The physiological effects of the reduced or anaerobic root zone are summarized in Figure 4.3. Other indirect effects should be mentioned as well. For example, plants may not exude water in the absence of light (e.g., at night) (guttation) when under water stress. Drew and Lynch (1980) review the relationship of waterlogging and plant pathogens and note that damaged roots may favor invasion by pathogens. The indirect effects of nutritional status may also influence plant susceptibility to invasion. Resistance mechanisms active in the healthy plant (for example, microrhizal associations and certain enzymatic pathways) may be impaired in the damaged plant.

C.2.b Exogenous Phytotoxins--

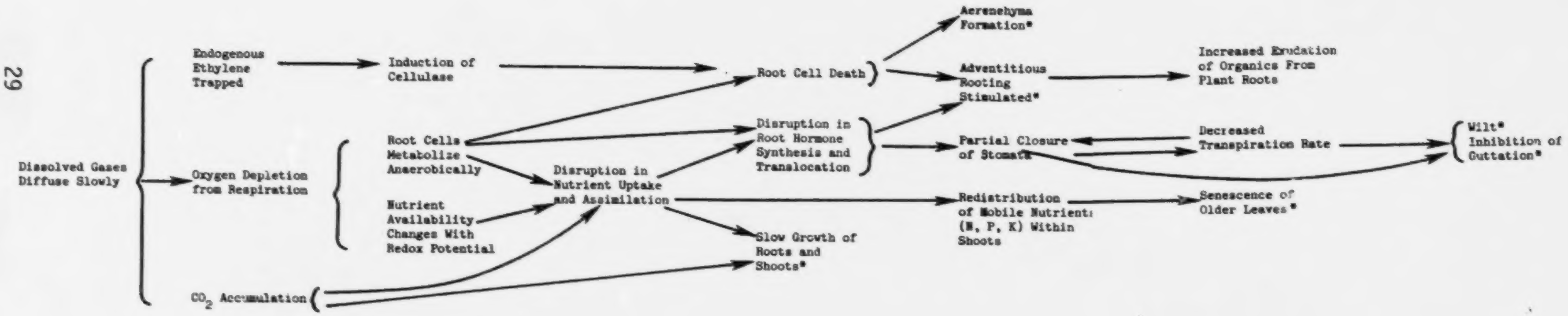
While the major components of sewage (biodegradable organics and solids) may be predicted from the size of a community, trace contaminants may vary widely. Table 4.3 shows the content of a number of metals in influent streams of municipal sewage. The concentrations of metals can vary over several orders of magnitude depending on the industrial sources. This section discusses the roles of metals and other trace level contaminants as potential plant toxins.

Plants require certain elements in their metabolism (Table 4.4). Non-essential elements are assimilated as well and are of concern regarding possible phytotoxicity and potential removal from the waste stream.

Bryan (1976) described the uptake of heavy metals by aquatic plants as a passive process, which can be indirectly influenced by metabolism. The kinetics of zinc uptake involve a rapid adsorption of Zn onto the cell membrane, followed by diffusion through the membrane and binding to proteins within the cell. The effect of zinc metabolism is seen in the amounts of protein available as binding sites.

Much of the research on plant responses to heavy metals has been conducted to assay the agronomic impacts of sewage sludge application. While this research is not directly applicable to the NFT process, it gives some indication of the role of metals as toxins. Cadmium and lead have been particularly well studied, due to their toxicity to humans. This research can provide general guidelines to relative rates of uptake and phytotoxicity of heavy metals to plants. However, most of the data are on crop plants grown in soil (Cunningham et al., 1975 and Chaney et al., 1975). The pH and organic matter content of soil exert a strong influence on the availability of metals to plants (John et al., 1972); consequently, the data from soil culture experiments are not readily transferable to hydroponic culture.

Hydroponic culture experiments have been conducted to assay the accumulation of certain heavy metals. Koeppe (1977) measured the uptake of lead and cadmium from hydroponic culture using crop plants. Uptake of both metals was considerable and varied with nutrient regime. After three days growth in 100 mg/ℓ Pb, corn roots had accumulated 10,600 μg Pb/g dry weight and corn shoots had accumulated 390 μg Pb/g dry weight. Cd uptake was similar,


Dissolved Gases Diffuse Slowly
Endogenous Ethylene Trapped
Oxygen Depletion from Respiration
CO_2 Accumulation
Induction of Cellulase
Root Cells Metabolize Anaerobically
Nutrient Availability Changes With Redox Potential
Disruption in Nutrient Uptake and Assimilation
Root Cell Death
Disruption in Root Hormone Synthesis and Translocation
Slow Growth of Roots and Shoots*
Aerenchyma Formation*
Adventitious Rooting Stimulated*
Partial Closure of Stomata
Redistribution of Mobile Nutrients (N, P, K) Within Shoots
Increased Exudation of Organics From Plant Roots
Decreased Transpiration Rate
Senescence of Older Leaves*
Wilt*
Inhibition of Guttation*

*Visible Symptom

Figure 4.3. Summary of physiological effects of the flooded root zone.

TABLE 4.3. POTENTIALLY TOXIC ELEMENTS FOUND IN RESIDENTIAL TRUNK SEWERS (From Davis and Jackson, 1975)

Element	Concentration (mg/ℓ)
Cd	0.007 - 0.019
Cr	0.008 - 0.09
Cu	0.12 - 0.21
Pb	0.075 - 0.12
Ni	0.014 - 0.09
Zn	0.20 - 0.25

TABLE 4.4. ESSENTIAL MINERALS FOR HIGHER PLANTS (From Keeton, 1980)

Element	Approx. no. of kilograms needed to grow one hectare of corn (of average yield)
MACRONUTRIENTS	
Nitrogen (N)	180
Phosphorus (P)	45
Potassium (K)	140
Sulfur (S)	85
Magnesium (Mg)	55
Calcium (Ca)	55
Iron (Fe)	2
MICRONUTRIENTS	
Manganese (Mn)	0.3
Boron (B)	0.07
Chlorine (Cl)	0.07
Zinc (Zn)	Trace
Copper (Cu)	Trace
Molybdenum (Mo)	Trace

but this metal was more readily translocated and the large gradient between the roots and shoots was not observed. Cd concentration of leaves of plants (crop and vegetable) grown in solution culture were reported by Page et al. (1972) (Table 4.5). The accumulation of Cd was proportional to the concentration of the metal in solution; leafy vegetables accumulated more of the metal in the edible portions.

TABLE 4.5. AMOUNTS OF CADMIUM ABSORBED BY VARIOUS PLANT SPECIES IN RELATION TO SOLUTION CADMIUM CONCENTRATION (From Page et al., 1972)

Solution concentration	Plant species								
	Corn	Turnip	Beet	Bean	Tomato	Cabbage	Lettuce	Pepper	Barley
μg/mℓ	Cadmium Concentration of Leaves, μg Cd/g								
Control*	0.29	0.32	0.30	0.12	0.11	0.75	0.14	0.98	0.10
0.1	90	160	280	9	58	—	—	—	—
0.25	234	270	321	27	115	—	—	—	—
0.50	165	394	295	34	138	—	—	—	—
1.0	227	469	326	35	174	212	384	104	75
2.5	—	—	419	—	334	420	430	180	86
5.0	—	—	755	—	591	714	588	314	110
10.0	—	—	1078	—	1122	822	751	578	175
	Total Cadmium Accumulated in Leaves, μg								
Control*	5.3	5.0	1.7	3.3	1.1	5.3	1.1	2.1	0.95
0.1	1262	1944	784	200	—	—	—	—	—
0.25	2111	1544	764	205	—	—	—	—	—
0.50	1713	1387	384	157	—	—	—	—	—
1.0	2184	1960	430	112	1183	1297	1219	133	437
2.5	—	—	302	—	1712	2142	1268	158	432
5.0	—	—	680	—	2438	3798	1058	314	522
10.0	—	—	323	—	3310	2754	788	474	525

*The concentration of Cd in the control solution was 0.0005 μg/mℓ.

Field data have been used to assay the uptake of heavy metals by aquatic plants. Mayes et al. (1977) in a study of a contaminated lake, concluded that Elodea canadensis can assimilate nonessential trace metals from surrounding water and sediments. Accumulation of metals by aquatic plants grown in an environment polluted by fly ash is reported by Guthrie and Cherry (1979) and is summarized in Table 4.6. Again, the aquatic plants are shown to accumulate metals.

TABLE 4.6. CONCENTRATION OF FLY ASH POLLUTANTS ABSORBED BY AQUATIC PLANTS. (From Guthrie and Cherry, 1979)

	Annual mean concentration, wet weight (ppm)			
Element	Sediment	Water	Duckweed (*Lemna* sp.)	Cattail (*Typha* sp.)
Al-Si	40,656	13	3,741	370
Fe	20,812	17	1,110	141
K	8,149	6.1	1,705	2,775
Mg	5,461	4.1	625	602
Ti	2,388	0.9	108	21
Ca	1,833	9.2	789	2,070
Na	687	7.7	289	65
Ba	294	0.7	34	67
Mn	96	0.07	80	425
Sn	84	0.1	18	7.0
Cl	84	3.8	213	847
V	63	0.04	5.1	0.6
Cu	51	0.4	8.1	5.4
Cr	38	0.2	5.2	1.3
As	19	0.06	5.8	0.4
Co	10	0.06	1.5	0.2
Zn	6.4	0.4	4.6	2.8
Se	6.1	0.1	1.7	3.9
I	4.6	0.08	1.2	0.4
Cd	1.7	0.1	1.4	0.4
Br	1.2	0.1	2.8	15
Sb	0.9	0.07	0.8	0.2
Hg	0.8	0.04	0.5	0.2

How the high levels of metals reported in these studies affect the plants is of concern. Foy *et al.* (1978) reviewed the physiological effects of metal toxicity in plants and pointed out that each metal causing phytotoxicity does not have a characteristic symptom. General symptoms are stunting and chlorosis. Chlorosis may appear to be an iron deficiency and can be induced by excesses of zinc, copper, nickel, and cadmium. Cd interferes with photosythesis of terrestrial plants, partly by reducing the concentration of photosynthetic pigments and altering their ratio; no data are available for aquatic plants (Alabaster and Lloyd, 1980).

Studies of the phytotoxicity of metals in nutrient solution culture have been few. Page *et al.* (1972) report Cd levels inducing a 50% reduction in growth of test plants (Table 4.7). Note that the sensitivity of the test plants varies over an order of magnitude. Table 4.8 summarizes several studies of phytotoxicity in floating or submergent aquatic plants. In general, the aquatic plants tested were most sensitive to copper and arsenic levels in the solution culture. These two metals have been commonly used as aquatic herbicides; their concentrations in domestic sewage are below damaging concentrations, but the concentrations that inhibit plant growth could be a problem in many wastes.

TABLE 4.7. SOLUTION Cd CONCENTRATIONS PRODUCING 50% GROWTH REDUCTION, VISUAL SYMPTOMS ASSOCIATED WITH 50% GROWTH REDUCTION, AND CONCENTRATION IN LEAF AT 50% GROWTH REDUCTION (From Page *et al.*, 1972)

Plant Tested	Cd Range Tested	Solution Concentration Producing 50% Growth Depression	Concentration of Cd in Leaf at 50% Growth Depression	Visual Symptoms Associated With 50% Growth Depression
	-------- μg Cd/mℓ	--------	μg Cd/g*	
Cabbage	0-10	9.0	800	†
Tomato	0-10	4.8	570	Chlorosis
Barley	0-10	5.6	120	†
Pepper	0-10	2.0	160	Chlorosis
Sweet corn	0- 1.0	1.2	230	Reddish-orange coloration of leaf margin, necrosis, and chlorosis
Lettuce	0-10	0.9	320	Chlorosis
Red beets	0-10	0.2	290	Wilting
Field beans	0- 1.0	0.2	22	Wilting
Turnips	0- 1.0	0.2	290	Chlorosis

*Oven dry weight, 70°C.
†No specific symptoms were associated with the reduced growth.

The literature on phytotoxicity of non-metallic substances to aquatic plants is limited. Table 4.9 summarizes the studies found in a brief survey. Oils are capable of spreading over large areas of air/water interface and plant surfaces and interfering with gaseous exchange.

In summary, comparison of Tables 4.3 through 4.8 indicates that aquatic plants should tolerate the levels of heavy metals found in typical municipal waste streams. Copper, cadmium, and arsenic levels may be of most concern, as aquatic plants are extremely sensitive to these metals.

C.2.c Plant Growth in Sewage Compared to Natural Habitats--

Seidel (1976) found that if certain plant species were grown in polluted water instead of in a natural habitat, changes in morphology, anatomy, and physiology of those species could result. For example, Alisma plantago-aquatica, which normally has a small storage bulb, grew to gigantic size in sewage and formed a very large storage bulb which was replaced by a new one

TABLE 4.8. EFFECT OF HEAVY METALS IN THE NUTRIENT SOLUTION ON GROWTH OF FLOATING OR SUBMERGENT AQUATIC PLANTS (page 1 of 2)

Metal	Test Concentration (mg/ℓ)	Plant	Effect	Reference*
Copper	0.25	*Myriophyllum spicatum*	50% reduction in root weight	1
	0.15	*Elodea canadensis*	50% reduction in photosynthesis	2
	0.46	*Elodea canadensis*	90% reduction in photosynthesis	2
	3.1	*Elodea canadensis*	50% damage to whole plant	2
	0.13	*Lemna minor*	50% damage to whole plant	2
Arsenic	2.9	*Myriophyllum spicatum*	50% reduction in root weight	1
	0.85	*Elodea canadensis*	50% reduction in photosynthesis	2
	2.6	*Elodea canadensis*	90% reduction in photosythesis	2
	0.90	*Elodea canadensis*	50% damage to whole plant	2
	0.15	*Lemna minor*	50% damage to whole plant	2
	11.5-143	Mixed aquatic plants (microcosm)	Net production of microcosm decrease to zero	3
Cadmium	7.4	*Myriophyllum spicatum*	50% reduction in root weight	1
	0.01	*Lemna valvidiana*	25% reduction in growth of whole plant	4
	0.05	*Lemna valvidiana*	80% reduction in growth of whole plant	4
	12.8	*Elodea canadensis*	50% reduction in photosythesis	2
	23.5	*Elodea canadensis*	90% reduction in photosythesis	2
	148	*Elodea canadensis*	50% damage to whole plant	2
	14.8	*Lemna minor*	50% damage to whole plant	2
	10.10-89.6	*Potamagoton crispus*	No reduction in biomass or photosynthesis	5
Chromium	1.9	*Myriophyllum spicatum*	50% reduction in root weight	1

TABLE 4.8. Continued (page 2 of 2).

Metal	Test Concentration (mg/ℓ)	Plant	Effect	Reference*
Mercury	3.4	*Myriophyllum spicatum*	50% reduction in root weight	1
	0.80	*Elodea canadensis*	50% reduction in photosynthesis	2
	1.69	*Elodea canadensis*	90% reduction in photosynthesis	2
	7.4	*Elodea canadensis*	50% damage to whole plant	2
	1.0	*Lemna minor*	50% damage to whole plant	2
Aluminum	2.5	*Myriophyllum spicatum*	50% reduction in root weight	1
Zinc	21.6	*Myriophyllum spicatum*	50% reduction in root weight	1
	8.1	*Elodea canadensis*	50% reduction in photosynthesis	2
	23.1	*Elodea canadensis*	90% reduction in photosynthesis	2
	22.5	*Elodea canadensis*	50% damage to whole plant	2
	67.7	*Lemna minor*	50% damage to whole plant	2
Silver	0.10	*Elodea canadensis*	50% reduction in photosynthesis	2
	0.18	*Elodea canadensis*	90% reduction in photosythesis	2
	7.5	*Elodea canadensis*	50% damage to whole plant	2
	0.27	*Lemna minor*	50% damage to whole plant	2
Thallium	1.43	*Elodea canadensis*	50% reduction in photosythesis	2
	2.75	*Elodea canadensis*	90% reduction in photosythesis	2
	2.0	*Elodea canadensis*	50% damage to whole plant	2
	0.008	*Lemna minor*	50% damage to whole plant	2
Lead	363	*Myriophyllum spicatum*	50% reduction in root weight	1

*References for Table 4.8: 1. Stanley, 1974; 2. Brown and Rattigan, 1979; 3. Giddings and Eddlemon, 1978; 4. Alabaster and Lloyd, 1980; 5. McIntosh *et al.*, 1978

TABLE 4.9. POTENTIAL PHYTOTOXICITY OF HYDROCARBONS AND OTHER ORGANIC COMPOUNDS.

Substance	Concentration	Plant	Effect	Reference*
Toluene	10 mg/ℓ	*Macrocystis angustifolia*	75% reduction in photosynthesis	1
Whole oils	100-10,000 mg/ℓ	Mixed algae cultures	Inhibition of photosynthesis and growth	2
Chloramines	6-25 μg/ℓ	Mixed aquatic plants (microcosms)	No changes in photosynthesis and respiration	3
Phenol	100 mg/ℓ	*Eichhornia crassipes*	No evidence of toxicity (Plants could remove 36 mg phenol/g dry weight)	4

*References for Table 4.9:
1. Environmental Protection Agency, 1976;
2. Vandermelen and Ahern, 1976;
3. Larson *et al.*, 1978;
4. Wolverton and McKown, 1976.

each year. Scirpus lacustris normally sheds its roots each year, but when grown in certain types of sewage, it did not. When cultured in unsettled sewage the plant did not produce roots; a rhizome, losing its scale-like leaves, took over mineral absorption. When a bed of this species was floated in sewage, there was no change in stem characteristics. In unsettled effluent from a fabric printing factory, this species produced ten to twenty times more biomass than when grown in uncontaminated water.

Seidel also found in this study that when S. lacustris was grown in an oxygen-poor medium, the aerenchyma expanded greatly; however, fiber content remained unchanged. Other anatomical variations observed were a change from uniform to irregular stomatal form and arrangement, and the formation of hydropods (water cells) on the epidermis when the plants were cultured in phenol-containing medium rather than in uncontaminated water.

C.3 Plant Adaptation to Sewage

C.3.a Mechanisms of Adaptation--

Despite the limitations to plant growth imposed by a polluted anaerobic environment, a number of plants can grow and thrive in environments of reduced oxygen. These kinds of plants would be ideal for "roughing treatment" in the initial stages of a NFT. Aquatic and wetland plants such as cattails, rice, water lilies, and mangroves are common examples. These plants possess a combination of morphological and biochemical adaptations to avoid or tolerate the conditions induced by the anoxic environment. These adaptations and examples of plants showing these characteristics are shown in Table 4.10.

Early investigations into mechanisms of resistance to the anaerobic environment were made by naturalists, who observed the morphology of wetland and aquatic plants and inferred function from structure. Two structures, lacunae (or aerenchyma) and adventitious roots, have been widely cited as adaptations to the reduced root zone.

Lacunae are longitudinal canals in the root cortex that extend into the plant shoot. The tissue in which the lacunae occur is called aerenchyma. Laing (1940) described lacunae in aquatic macrophytes. Oxygen diffusion from the aerial portions of the plant through the lacunae and to the roots was postulated as the mechanism of resistance to anaerobiosis, as anaerobic metabolism and the accumulation of phytotoxic end products could be avoided. However, Crawford and Tyler (1969) argued that lacunae could be an adaptation to minimize the amount of respiratory tissue per volume of root, and consequently reduce the overall demand for oxygen in the plant.

Indirect evidence that oxygen can be transported from the aerial portions of plants to the roots was provided by Armstrong (1967), who demonstrated oxygen diffusion from the roots of bog plants to the rhizosphere when grown in anaerobic soils. Oxygen loss from roots has other important implications. If a microzone around the roots is oxidized, the plant roots will avoid contact with reduced phytotoxic substances (e.g., metals, sulfides, and organic acids which are generally rendered insoluble in an oxidized environment) in the soil. Note that solubility is a function of not only the oxidation-reduction state but also pH and competing liquid concentrations.

TABLE 4.10. PLANT ADAPTATIONS TO SURVIVE AN ANOXIC ENVIRONMENT.

Adaptation	Examples of Plants Exhibiting Adaptation
Morphological	
A. Lacunae to transport oxygen from shoot to root	Nuphar luteum (water lily) Spartina alterniflora (marsh grass)
B. Adventitious roots to facilitate ethanol diffusion	Zea mays (corn), Helianthus annuus (sunflower), Triticum sp. (wheat), Oryza sativa (rice)
C. Storage tubers to overcome energy limitations of glycolysis	Sagittaria latifolia (arrowhead)
Biochemical	
A. Alternative fermentative pathways to minimize ethanol accumulation	Senecio aquaticus (ragwort, groundsel) Veronica peregina (speedwell)
B. Nitrate reductase to use nitrate as an electron acceptor	Lemna minor (duckweed) Rumex acetosa (green sorrel) Mentha aquatica (mint)

Armstrong suggests a physiological classification of plants based on their oxidizing capabilities drawn in part on the work of Conway (1937) and Stolzy et al. (1962). The series consists of: (1) those which can tolerate very strongly reducing conditions because of considerable root oxidizing power and internal oxygen supply (e.g., Menyanthes trifoliata and Oryza sativa; (2) those whose oxidizing capabilities are less (e.g., Molinia coerulea); (3) those which, although able to receive internal respirating oxygen, are unable to oxidize even mildly reduced soil; (4) partially soil-oxygen dependent plants; and finally, (5) those mesophytes with high soil-oxygen requirements (Stolzy et al., 1961).

Direct measurement of gas flux through the lacunae of Nuphar lutea was recently reported by Dacey (1980). Dacey measured oxygen movement at rates up to 50 cm/minute through the lacunae, and concluded that gas movement was by mass flux, not by diffusion.

The second frequently cited adaptation to the anaerobic root zone is the presence of adventitious roots. Jackson (1955) determined that plants with adventitious roots showed fewer symptoms of stress and a faster recovery when flooded with low oxygen water. The response of the plants was independent of depth of flooding. Adventitious roots facilitate the diffusion of ethanol, a toxic end product of glycolysis, into the rhizosphere; Crawford (1978) considers this to be the mechanism of resistance.

Root porosity (the fraction of the root filled with gas) is higher in adventitious roots than in primary roots (Yu et al., 1969). Consequently, increasing the number of adventitious roots will increase the overall root porosity of a plant. Adventitious rooting was induced in sunflowers, wheat, and corn when the plants were flooded (Yu et al., 1969); therefore, plants not normally grown in flooded conditions were shown to survive by increasing oxygen and ethanol diffusion through the new, porous roots.

The adaptations described thus far allow plants to grow in the anaerobic environment by avoiding glycolysis (by oxygen transport from the shoots) or by eliminating the toxic end product of glycolysis (by ethanol diffusion through adventitious roots). Crawford (1978) suggests that the tubers of aquatic plants are a third morphological adaptation to anaerobic conditions. The large supply of carbohydrates present in the tubers would help compensate for the inefficiency of energy production via anaerobic metabolism until the shoots emerge above the sediment surface.

Another adaptation to the anaerobic environment is the use of biochemical pathways that do not form ethanol. Plants resistant to anaerobiosis minimize the accumulation of ethanol by using alternative fermentative pathways and by minimizing the conversion of acetaldehyde to ethanol (Crawford and Tyler, 1969; Crawford, 1978).

The alternative fermentative pathway forms malate, an organic acid, from glucose via phosphoenolpyruvate (PEP) carboxylase (Crawford and Tyler, 1969). The organic acid is less toxic than ethanol. The conversion of acetaldehyde to ethanol is catalyzed by an enzyme, alcohol dehydrogenase (ADH). Levels of ADH were measured in a series of experiments on plants resistant and non-resistant to anaerobiosis; the root cells of non-resistant plants showed a high level of ADH when the roots were flooded, while resistant plants showed no increase in the enzyme (Crawford and Tyler, 1969).

Crawford and Tyler (1969) further proposed that malate may accumulate in flood-resistant roots because of the absence of malic enzyme. However, Davies et al. (1974) found that malic enzyme was present in a large number of resistant and non-resistant plants. Crawford later suggested that malic enzyme activity in resistant plants is inhibited when the roots experience low oxygen concentrations (Crawford, 1978).

Several objections have been raised to the metabolic theory of flooding tolerance. Drew and Lynch (1980) point out that a significant amount of ethanol is produced in all plants during glycolysis, and that resistance may reflect the ability to eliminate or tolerate ethanol itself. Smith and ap Rees (1979) reported the results of enzymatic assays to clarify the pathways of carbohydrate fermentation in resistant plants. They concluded that the catalytic activities of ADH, PEP carboxylase and malic enzyme were all appreciable in the resistant plant roots; when grown anaerobically, ADH levels increased but PEP carboxylase was not detectable. In experiments with a labelled substrate (sucrose), the end products of fermentation were ethanol and lactate, with minimal malate levels. Clearly, futher experiments are required to reconcile these different results.

Use of an alternative electron acceptor in the absence of oxygen is yet another adaptation to life in an anaerobic root zone. Garcia-Nova and Crawford (1973) suggest that nitrate may be used in this manner, citing as evidence the increased level of nitrate reductase activity in flooded roots of resistent plants.

C.3.b Indicators of Adaptation to Anaerobic Conditions--

Plants clearly differ in ability to tolerate anaerobic conditions in the root zone. Knowing what properties, if any, resistant plants have in common would simplify the search for plants able to thrive under the proposed NFT system. One obvious indicator of tolerance is the plant environment; resistant plants are those which grow in anaerobic environments. However, experiments in which crop plants were flooded indicated that plants normally grown in aerated soil showed varying degrees of flooding tolerance.

Plant species are attractive for use in the NFT system for reasons other than survival (for example, removal of nutrients or particulates) or production of a valuable crop. An indicator of resistance to anaerobiosis in the root zone would help screen candidate plants chosen for additional qualities.

The research into metabolic pathways of carbohydrate fermentation discussed in the previous section suggests several possible biochemical indicators of tolerance to anaerobiosis. Crawford and Tyler (1969) noted that alcohol dehydrogenase (ADH) induction upon flooding was greater in non-tolerant plants than tolerant plants. This response has been suggested as an indicator (Crawford, 1978). Chirkova (1978) noted a direct relationship between the affinity of ADH for its substrates, ethanol and acetaldehyde, and flooding tolerance.

Garcia-Novo and Crawford (1973) suggest that the activity of nitrate-reductase in roots may be a good index of flooding tolerance. The enzyme level was increased in all their test species, but increased to highest levels in the flooding tolerant species.

Bartlett (1961) noted that the accumulation of iron oxides on plant roots is correlated with the ability of plant roots to oxidize a small zone of the rhizosphere. Plants that assimilated iron into the aerial parts of the plants were not as resistant to flooding.

Another indicator of resistance to anaerobic root zones has been proposed by Armstrong (1978), who measured the ability of roots of several plants, mainly forage crops, to grow into reduced (paddy) soils. He found that root penetration was highly correlated with the plant's ability to oxidize a dye, α-naphthylamine.

Use of a dye to indicate ability to transport oxygen into roots has been proposed by Philipson and Coults (1978). Indigo-carmine dye is suggested; the dye is colorless when reduced and blue when oxidized. A blue halo will appear around the root of a plant capable of oxygen transport.

Although the number of proposed indicators suggests that rapid screening of plants for tolerance characteristics is quite feasible, a note of caution is warranted. Tolerance to flooding appears to vary greatly between species and even varieties of the same species. Linhart and Baker (1973) tested the physiological response to flooding of different individuals of a species of a weed (Veronica peregina L.) growing in an area that was flooded each year from December through March. Plants raised from parents that germinated under water in the center of the pond and grew for several weeks on flooded soil accumulated malate when flooded. Those plants raised from parents collected from the edge of the pond did not accumulate malate. Clearly, habitat remains an important indicator of tolerance to anaerobiosis.

C.3.c Identification of Plants Tolerant To NFT Sewage Environment--

Using the descriptions of suitable plant characteristics, it is possible to identify plants that may be grown in an NFT system using sewage. A compilation of more suitable plants is shown in Table 4.11. This table also includes a description of plants' growth forms and distributions.

C.4 Environmental Factors Affecting Tolerant Plants

C.4.a Effect of Water Level on Growth of Emergents--

Emergent aquatic plants, by definition, have shoots growing above and roots growing below a body of water. The natural habitat of emergent aquatic plants, however, ranges from shallow water and continually saturated soils to periodically inundated (tidal) areas, to seasonally dry lowlands, and meadows. Fluctuations in water levels and consequent changes in aeration of the rooting zone are thus conditions to which this group are specifically adapted. For this reason, the emergents are ideal for use in wastewater treatment in NFT systems where the root mass is partly exposed to the air and partly surrounded by an anaerobic medium.

Nutrient availability is greatly enhanced in anaerobic substrates where the reduced form of ionic species occurs. Uptake of toxic levels of many substances by emergent plants in this reduced zone is avoided by diffusion of oxygen and oxidizing compounds from the roots into the substrate. Nutrients and potential plant toxins are precipitated and adsorbed to particulate matter in this oxidized zone of the actively growing root tip; the oxidized zone decreases in size toward the basal portions of the root, where presumably uptake occurs. Fluctuating water levels would appear to have a similar

TABLE 4.11. EMERGENT SPECIES TOLERANT OR POTENTIALLY TOLERANT TO NFT SEWAGE ENVIRONMENT (From Fassett, 1957; Muenscher, 1944; and Cook *et al*., 1974) (page 1 of 7).

Species	Growth Form	Distribution	Notes
1. Cattail Family (Typhaceae)			
Typha latifolia (Common cattail) *Typha augustifolia* (Narrow leaved cattail)	Stout, upright plants up to 6 ft (2 m) tall, forming dense colonies. Spreads mostly by creeping rhizomes. Flowers in May/June. Monoecious, perennial. Hybrids of these two species where they are found growing together.	Cosmopolitan; Newfoundland to Alaska, south throughout most of U.S. and into Mexico	Pistillate spike often gathered for arrangements; persists until winter. Hairy down of spike is used for packing material. Leaves are resistant to decay and absorb water and swell. They are harvested extensively in the Fall and stacked for drying. Uses include caulking, packing nursery stock, weaving. Rootstocks are rich in starch.
2. Grass Family (Graminac)			
Phragmites australis (Reed, Reed grass)	Stems are stout, upright; reach 16 ft (5 m); from coarse, scaly rhizomes; sometimes with long stems creeping extensively over moist soil surface. Perennial; persistent throughout fall and winter. Flowers in August/September.	Widespread; throughout S. Canada and the U.S., except in S.E. U.S. In freshwater and brackish marshes, around springs, and along shores of lakes and streams.	

TABLE 4.11. Continued (page 2 of 7).

Species	Growth Form	Distribution	Notes
2. Grass Family (cont.)			
Spartina pectinata (Cordgrass) *S. alterniflora* (Saltmarsh cordgrass) *S. patens* (Saltmeadow cordgrass)	Erect stems, 1-2 m tall; from stout, scaly, cordlike rhizomes. Leaves long and tough. Two forms of *S. alterniflora*: a short form (0.3-0.4 m) on high marsh; a tall form (1.2-2.0 m) on intertidal zone. Optimum pH 4.7-7.8. Perennial; scaly rhizomes that may comprise the bulk of total plant biomass (depending on age of stand and season).	*S. pectinata* found in shallow, sandy lakes and freshwater marshes, also in brackish marshes along Atlantic coast. Widespread except in south. *S. alterniflora* found in salt marshes along seacoast from Maine to Texas. *S. patens* in salt marshes along Atlantic coast; rare in inland marshes in New York and Michigan.	Extensive salt meadows of *S. patens* along the Atlantic coast are sometimes cut for 'salt hay.' Formerly used extensively for packing and bedding material.
Phalaris arundinacea (Reed canary grass)	Slender grass up to 2 m tall, generally in dense colonies. Erect stem. Perennial.	Newfoundland to Alaska, south to North Carolina, Missouri, and California. Grows in areas subject to inundation.	Planted as a forage grass on marshy meadows in many areas.

TABLE 4.11. Continued (page 3 of 7).

Species	Growth Form	Distribution	Notes
2. Grass Family (cont.)			
Zizania aquatica (Wild rice, of East) *Z. aquatica* var. *augustifolia* (Northern wild rice) *Z. aquatica* var. *interior* (Large wild rice, of midwest)	Stout, erect stem; 2-3 m long. Many 'prop' roots emerge from lower nodes. Roots easily pulled up. Leaf blades flat, 1-5 cm wide. Inflorescence 30-50 cm long, monoecious; annual. Var. *augustifolia* 0.5-1.5 m tall; leaves 4-12 mm wide. Var. *interior* 0.9-3 m tall; leaves 1-4 cm wide. The latter two varieties intergrade where their ranges overlap, but ordinarily are distinct. Seeds do not withstand drying; for purposes of propagation it must be stored moist (in water or wet moss) at 1-3°C until planting.	*Z. aquatica* found in brackish water along coast; South Maine to Florida; inland to North Indiana and E. Wisconsin. Var. *augustifolia*, South New Brunswick to N. Maine, west to N. Minnesota and N. Indiana. Var. interior, Indiana, and South Minnesota to Nebraska and Texas. All forms require a soft, fertile bottom; inland, this group is found in shallow water, lakes, slow streams, and edges of marshes.	Seeds from natural stands are gathered for human consumption and the plant is grown commercially. It is introduced to many areas as food for waterfowl. See Chambliss (1940).
Zizaniopsis miliacea (Southern wild rice)	Perennials with creeping rhizomes, culms 1-3 ft high. Leaf blades 1-2 cm wide; panicles 30-120 cm long.	In North and South America; semi-aquatic to aquatic; mostly in marshes, creeks, and river banks.	
Calamagrostis canadensis (Bluejoint)	Tall, slender grasses, from extensively creeping rootstocks, making swales. Inflorescence is open in *C. canadensis*.	*C. canadensis* found in moist places; Greenland to Alaska; south to Maryland, North Carolina, Missouri, Kansas, Colorado, Arizona, and California.	

TABLE 4.11. Continued (page 4 of 7).

Species	Growth Form	Distribution	Notes
2. Grass Family (cont.)			
Arundo donax (Reed, Giant reed)	Robust; stem 2-6 m, many-noded; hollow. Leaf blades up to 70 mm wide and up to 1 m long; inflorescence dense, erect, 30-60 cm long. Rhizome thick, creeping, knotty.	Introduced to the U.S. from warm regions of the Old World; occurs along rivers, irrigation ditches, streams; on river banks, occasionally in marshes.	The culms, or flowering stems, are used for lattices, mats, and screens in the construction of adobe huts; they are important as sources of musical reeds (for clarinets, organ pipes, etc.) and for industrial cellulose.
Arundinaria tecta (small cane)	Arborescent or shrubby, simple or branching stems, 1 to 5 m tall. Flowers in May/July. Perennial. Lacunae in rhizomes reported by McClure (1963) (not in A. macrosperma). Also called switch-cane, scutch-cane, reed.	From Maryland to Indiana and Missouri, Florida, and Texas; in swamps and moist soil. So-called "cane-brake."	Both species of Arundinaria, commonly known as bamboo, are used for construction, furniture and decorative purposes; the young shoots are also edible.
Arundinaria macrosperma (Giant cane, also called A. gigantea)	Possibly intergrading species with A. tecta; this plant is the largest member of the grass family. colonies in low, moist	From southern Ohio, Illinois and Missouri, south to Florida and Texas. Extensive colonies in low, moist woodlands and along streams and rivers.	

TABLE 4.11. Continued (page 5 of 7).

Species	Growth Form	Distribution	Notes
3. Sedge Family (cyperaceae)			
Carex spp. C. aquatilis C. comosa C. lanuginosa C. inflata C. vesicaria C. crinita C. lurida C. lupulina C. hystricina C. pseudo-cyperus	A large and complex genus, differentiated by the nature of the perigynium (sac enclosing the nutlet). The most common species are listed, and may be described as follows: grasslike perennials; rhizomatous or tufted; stems solid usually leafy and trigonous; up to 2 m high. Inflorescence varies from a much branched panicle to a simple spike.	About 1,000 species world-wide; cosmopolitan, mainly temperate. Most species occur in damp places (wet meadows, swales); a few are aquatic.	
Cladium jamaicensis (Saw grass) C. mariscoides (Twig rush)	Plant is 1-3 m high; leaves broad (5-10 mm wide) with serrate-spiny margin and lower midrib. C. mariscoides smaller (0.3-1 m high, leaves narrow (1-3 mm wide), not serrate-spiny.	C. jamaicensis is found chiefly on the Atlantic coastal plain (Virginia to Florida) and along the Gulf coast to Texas. It is the dominant plant in large areas of the Florida Everglades. C. maris coides is a northeastern species, also found along the Great Lakes. Both species grow in fresh or brackish waters in swamps, marshes, and shallow water.	C. jamaicensis has been considered as a source of fibers for paper-making, and C. mariscoides is used extensively for thatching.

TABLE 4.11. Continued (page 6 of 7).

Species	Growth Form	Distribution	Notes
3. Sedge Family (cont)			
Cyperus spp. C. papyrus C. rotundus C. articulatus C. ochraceus	C. rotundus perennial; numerous slender rhizomes with small tubers; stems 20-50 cm, smooth; leaves 3-6 mm wide, equal in length to stems.	Widespread in tropics, north to Virginia and occasionally adventive further north.	
Scirpus acutus (Hardstem bulrush, Big bulrush)	Circular stem, 3-10 mm thick, up to 4 m high; coarse, firm, dark green. Arising from thick, creeping rhizome without tubers. Flowers in July/August; perennial.	Widespread in U.S., except for southeast. Common in hard water; so-called "Tule marshes" in calcareous regions. Also in shallow water.	
S. americanus (Chair-maker's rush, shore rush, 3-square)	Stem sharply triangular, mostly solid; 2-5 mm thick, up to 1.2 m tall. In scattered groups arising from long, thick rhizome without tubers. Flowers in July/August; perennial.	Widespread throughout S. Canada and U.S. Abundant in shallow water or sandy shores of lakes, ponds, and streams; often in brackish water eastward.	
S. validus (Softstem bulrush, Great bulrush)	Stem soft, light green, round, 1-4 m tall; 0.8 - 2.5 cm thick at base; arising from stout creeping rhizomes. Flowers July/August; perennial.	Widespread, Newfoundland to S. Arkansas, south to Georgia, Missouri and California. In brackish or fresh water up to a meter or more deep, and in wet meadows and marshes.	

TABLE 4.11. Continued (page 7 of 7).

Species	Growth Form	Distribution	Notes
4. Arum Family (Araceae)			
Acorus calamus (Sweet flag)	Leaves and flowering stems up to 1.5 m tall, in loose colonies. Long, swordlike leaves arising from stout, creeping rhizome. Flowers in June/July; perennial.	Widespread; Nova Scotia and Quebec to Alberta and Oregon; south to Florida and Texas. In marshes and edges of lakes and streams. May persist and even spread in partially drained marshy fields which become relatively dry in summer; flowering or fruiting may not occur in such a habitat, but abundant quantities of viable seeds are produced in shallow water or spring-fed marshes.	Valued for its aromatic fragrance; used historically for therapeutic and related purposes. The fragrance of tangerines is due to a volatile oil present especially in the rootstocks; the leaves are also fragrant and were often strewn on floors. Used to flavor beer, gin, and other drinks; also to scent perfumes and cosmetics. See Sculthorpe (1967).
5. Rush Family (Juncaceae)			
Juncus effusus (Soft rush)	Stems up to 1.5 m growing in tussocks. (of up to several hundred) and arising from stout rhizome. Flowers July/August; perennial.	Throughout U.S. and S. Canada, in meadows and marshes.	

effect on redox (reduction/oxidation) potential and nutrient availability in the rooting zone.

A number of studies have been conducted concerning the tolerance of aquatic plants to submergence; a review of distribution and dominance of a number of species as related to substrate, water level, and light preferences was published by Spence (1967). Haslam (1970) discussed the biology, ecology, and production of the common reed (Phragmites australis) as related to water and water levels. Gorham and Pearsall (1956) presented information on water level, pH, nitrogen, and organic matter content, and conductivity in reed stands; they found that a declining water table was detrimental to production, but depth of the water above the soil surface was not crucial. Shoot production was greatest where mineral content of the water was high.

Cattails are generally dominant where the water level is greater than 15 cm; optimum depth is 0.25 - 1.0 m. The reed is a poor competitor, but grows well at water levels from 0.3 m below to 1.5 m above the soil surface and often colonizes new areas. Scirpus olneyi (bulrush) requires water levels from 5 to 10 cm above the soil surface in order to become established, and is found at water levels of -0.75 m (below the soil surface) to +6 m; Sipple (1979) discusses the biology, ecology, production, propagation, and management of this species.

Production of the sedge Carex is decreased with increasing water level, and this genus is generally found in shallower water than the bulrushes.

Generally, the grasses are found at the water's edge rather than in standing water; soils in cordgrass habitats are normally saturated, however, and reed canary grass has been reported to tolerate flooding as well (Broome et al., 1975; Byers and Zeiders, 1976; Bole and Bell, 1978).

C.4.b Effects of Temperature on Emergents--

Temperature tolerances for plant activity generally range between 0° to 45°C, differing with species and developmental stage. Temperate zone species may require daily and/or seasonally low temperatures, while tropical species may be grown at a uniformly warm temperature. The tropical plants may be susceptible to chilling injury at above-freezing temperatures and be killed at the first frost, but certain temperate species may freeze solid without permanent injury. High temperature stress is reported to be more dependent upon length of exposure than is cold-induced injury (Levitt, 1972).

The widespread distribution of most aquatic emergents attests to their tolerance of a broad range in air temperature. The stabilizing effect of associated water bodies on air temperature may also be a factor in this wide-ranging distribution.

Most emergents require a cold period and the resulting dormancy. Aerial shoots of Phragmites die in the fall, but rhizome growth is at a maximum in early autumn and continues during the winter; dormancy may last from three to six months depending on climate. Similarly, the successful cultivation of cattails, reeds, and sedges involves harvesting the rhizomes in the fall and storing them at 1° to 3°C for at least a month before planting. Alternatively, dormant rhizomes can be harvested during the winter (Dykyjova and Veber, 1978).

Growth of reeds and sedges is increased at higher temperatures, and stands are generally taller over a hot summer than over a cooler summer. The optimal air temperature for root production for a temperate species of bulrush is 10°C, while a tropical species of bulrush requires 20°C. Similarly, yield of a temperate species of Carex is greatest at 15°C, while the optimum for purple nutsedge (Cyperus rotundus) found in warmer climates, is 32°C (Wills, 1975; Gomm, 1978). Tuber development of purple nutsedge is also greatest at 32°C; ten-day lethal temperatures are 0° and 45°C (Palmer, 1961; Horowitz, 1972). The tubers of the nutsedge will not sprout when the temperature is below 19°C. Additional information on the temperature requirements of purple nutsedge is reported by Shamsi et al. (1978). Reed canary grass grows well at air temperatures of 15° to 30°C; requirements for cordgrass are reviewed by Turner (1976) and Teal (1962).

Water temperatures of 30°C are optimal for the growth of cattails, but survival is poor at 35°C (Jones et al., 1979). Vlehlova and Pribil (1978) reported water temperatures of 11° to 16°C in Czechoslovakian reedswamps through the growing season, and between 3° and 4°C in winter. No information was found on the effects of water temperature on sedges or on grasses.

Soil temperature requirements of cattails have not been described, and no work has been reported on aquatic grasses; however, reeds and sedges have been studied. Haslam (1970a) presented much information regarding the propagation of Phragmites and found that: (a) horizontal rhizomes are undamaged by frosts; (b) buds of vertical rhizomes (formed at the end of horizontal rhizomes) are frost-sensitive and give rise to aerial shoots; and (c) lethal temperatures vary with season.

C.4.c Light Intensity--

The effect of light intensity on cattails, rushes, and cordgrasses is not known, but sedges, reeds, and canary grass have been studied. Optimum illumination for purple nutsedge at 32°C is 100,000 J/m^2-h light energy (Gomm, 1978). Shading by taller shoots inhibited reed growth (Haslam, 1972, 1973), but forced new shoot development in bulrush (Ondok, 1972). Purple nutsedge tubers were shown to sprout more frequently in light than in dark (Shamsi et al., 1978).

Yield of reed canary grass grown at 15°C increased as the irradiance was increased from 15,000 to 150,000 J/m^2-h, but low light levels (15,000 J/m^2-h) and high temperatures were associated with nitrate and ammonium accumulations to levels which could become toxic to livestock (Gomm, 1978; 1979).

C.4.d Photoperiod—

The effects of photoperiod on reeds, rushes, bulrushes, and nutsedges are not known. McNaughton (1966) showed that cattail rhizome production was greatest with short days (12-14 hr versus 16 hr) and day/night temperatures of 21°C/7°C. Tuber formation in Carex spp. is induced by short days (10 hr) and inhibited by long days (18 hr) (Horowitz, 1972).

Vegetative growth of aquatic grasses has also been shown to respond to changes in photoperiod. A combination of long (16 hr) days and day/night temperatures of 30°C/25°C promoted aboveground production in reed canary grass; below ground production was stimulated by short (9 hr) days and lower temperatures (Sato and Audo, 1976). Cordgrass seedling biomass was greater with longer (12 hr) day length, while underground production and increased chlorophyll content was induced by a nine-hour photoperiod (Seneca and Broome, 1972).

In general, a short-day (9 to 10 hr) photoperiod is probably optimum for underground production in the grasses and sedges, while 12 to 14 hours of daylight are needed for below ground development in the cattail.

C.5 Plant Growth Characteristics

C.5.a Assimilation of Nutrients and Yield—

Annual mean production in a temperate Typha marsh is about 23 tonnes dry weight/hectare-year (t/ha-yr) and 76 to 96 t/ha-yr in a reed swamp (Cyperus papyrus) (Westlake, 1963; Thompson, 1972). Sculthorpe (1967) presented data estimating ash content in floating and emergent communities at 11.5 percent (i.e., 88.5% organic matter) on a dry weight basis. This estimate results in organic matter (OM) production of about 20 t/ha-yr for Typha and from 67 to 85 t/ha-yr for Cyperus marshes. These values may be compared with organic matter production of temperate and tropical agricultural annuals (20 and 27 t/ha-yr, respectively), and of temperate and tropical submerged macrophytes (5 and 15 t/ha-yr, respectively) (Westlake, 1963). It is possible that continuous availability of nutrients in a wastewater treatment NFT could result in substantial yield increases over those reported above.

Pearsall (1920), however, gave a considerably wider range of organic matter content in emergents (Table 4.12), with Carex spp. having the highest percent OM and Typha latifolia the lowest, 89.4 and 34%, respectively. These high ash contents lead to dissolved salt management potentials with the NFT.

Boyd and Hess (1970) found that standing crop (dry weight biomass) of Typha was strongly correlated with the dilute and soluble phosphorus content of the hydrosol (the saturated or submerged soil) and the water standing above the hydrosol. They also found significant correlations between environmental levels of several nutrients (N, P, Ca, Mg, K, Na, S) and tissue concentrations of those nutrients. Tissue concentrations rose faster than standing crop (considerably more than 50% net mineral accumulation occurred before 50% of the maximum dry matter crop was produced) (Boyd, 1970).

TABLE 4.12. ORGANIC MATTER CONTENT OF SOME EMERGENTS (From Pearsall, 1920).

Emergent	Percent Organic Matter	
	Mean	Range
Typha latifolia	34.0	20-50
Scirpus and *Phragmites*	44.7	20-65
Equisetam fluviatile	60.9	40-80
Carex spp.	89.4	80-95

The chemical composition of emergent aquatic plants is directly related to the composition of the substrate in which they grow, and thus is a valuable indicator of the capacity of these plants to remove various elements from wastewater. Most data are reported for aboveground biomass only; ranges of nitrogen and phosphorus content are presented in Figures 4.4 and 4.5, and the percentage of those and other elements in emergent shoots are listed by Stephenson *et al*. (1980). Heavy metal content of cattails, reeds and rushes, sedges, and grasses is also given by Stephenson *et al*. (1980).

Mineral and OM content vary with season and specific organ. Younger tissues are generally found to have higher OM content and mineral concentration than older tissues, and for that reason multiple harvesting has been considered. It is also known that in *Phragmites*, sodium, calcium, and magnesium tend to be accumulated predominately by underground organs, but nitrogen, phosphorus, and potassium are distributed more evenly throughout the plant (Ulehlova *et al*., 1973). N, P, and K are released to the surrounding medium by senescing tissues, while Na, Ca, and Mg are translocated to shoot tissue. Thus, for most efficient removal of nitrogen and phosphorus, it is recommended that aboveground portions be harvested periodically (prior to senescence). In order to maximize development of the root mass, which in *Phragmites* generally lives for more than three years, it appears to be most efficient to harvest aboveground portions periodically and to harvest the entire plant after the end of the third growing season. This would, of course, require a rotating system of cultivation with one-, two-, and three-year-old plants. Actual long-term life cycle and propagation studies of *Phragmites* in the NFT have not been done, so additional cultivation systems might work successfully.

Cattails are characterized by a two-year growing cycle. Most of the shoots are fertile in the second growing season, and rhizomes connecting these shoots are dead at the end of that year. Cattails exhibit two periods of maximal biomass increase; one from July to early August, with peak increments in rhizome biomass and leaf area; and one from late September to October, when there is an accumulation of reserves in the underground organs (Fiala, 1973). The relative growth rate of roots exhibits two maxima

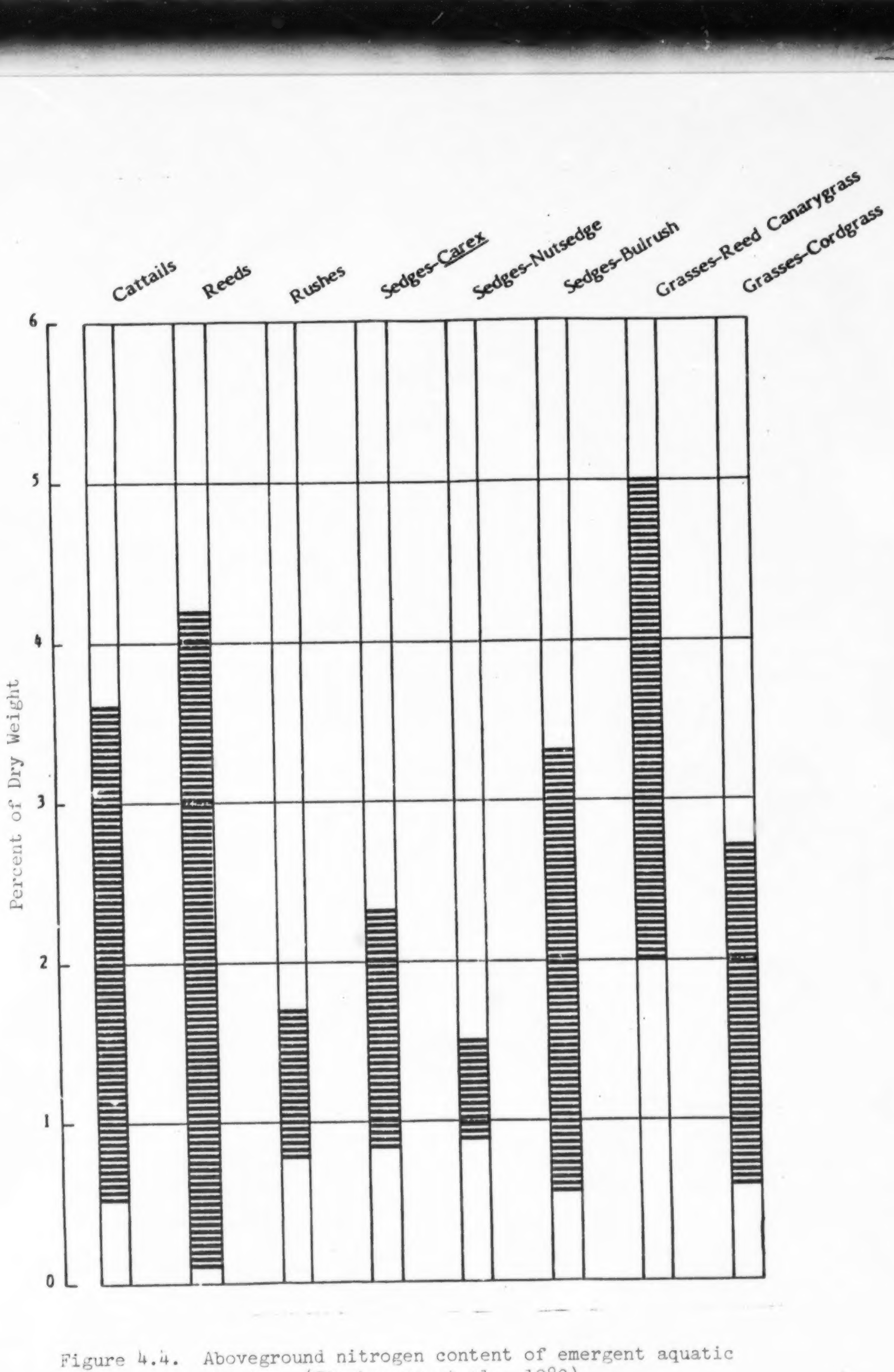


Figure 4.4. Aboveground nitrogen content of emergent aquatic plants. (Stephenson *et al.*, 1980)

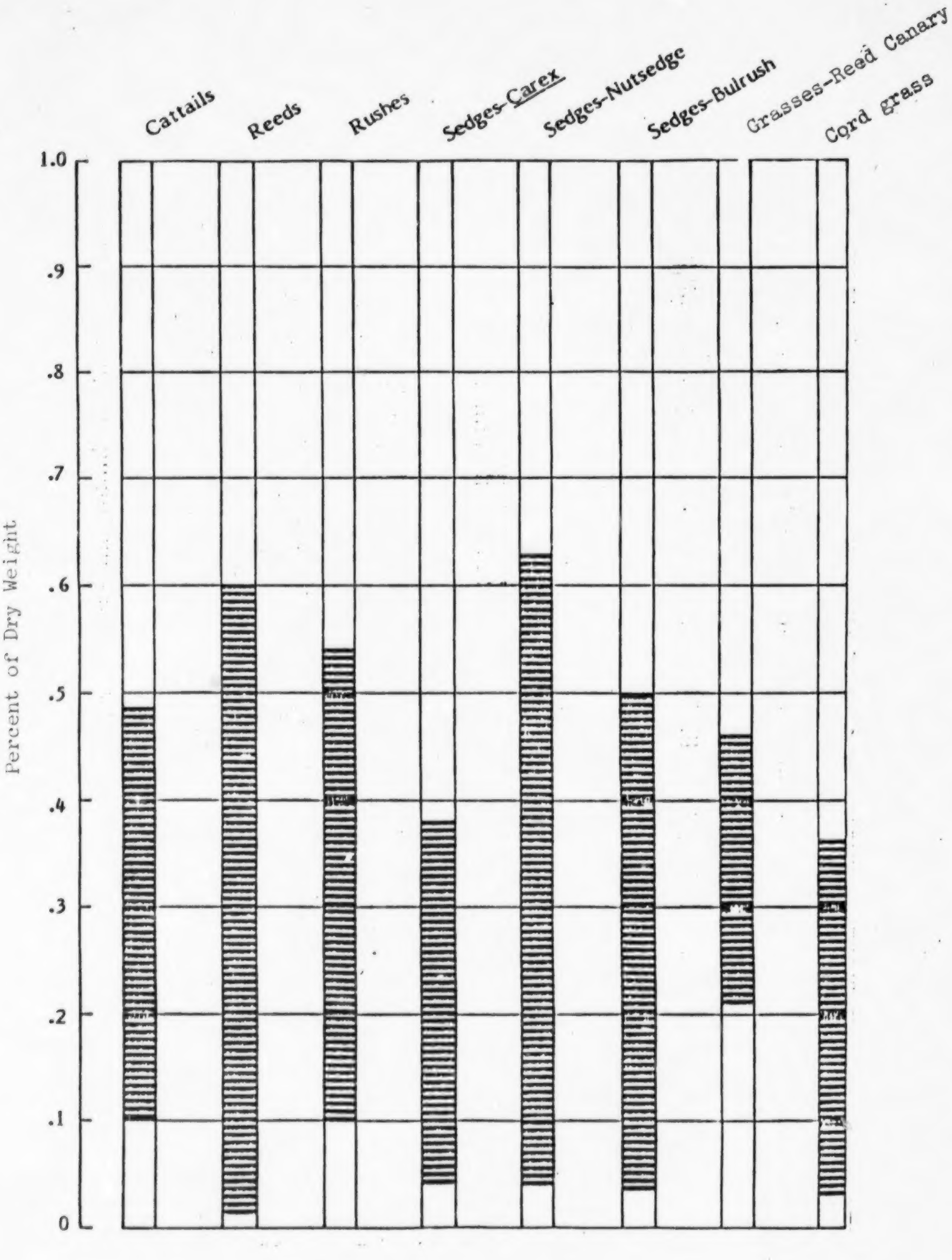


Figure 4.5. Aboveground phosphorus content of emergent aquatic plants (Stephenson *et al*., 1980)

(summer and autumn), but that of underground shoot bases and rhizomes peaks only once in summer. The rate of increase in bulk density of first-year Typha rhizomes increases markedly from August through October; this increase also occurs in both new and old rhizomes during that period of the second growing season but is less marked. This phenomenon is associated with the mobilization of reserves to those portions of the plant.

Estimates of yield have been compiled for a number of emergents, including the cattails, reeds, rushes, sedges, and grasses. Figure 4.6 illustrates the variations in peak aboveground biomass that can be expected under natural conditions. These data show that in natural stands the cattails and reeds can produce the greatest aboveground biomass. Similarly, peak belowground biomass in natural habitats is greatest in the reeds, rushes, and certain grasses (Figure 4.7) and may be twice that of the aboveground yield. Note that in an NFT the root mass would also be harvested. Reported values for peak biomass (aboveground and belowground) are slightly lower for both cattails and reeds in hydroponic culture; however, the reeds appear to be a promising group in terms of yield for NFT. It appears that harvesting the total plant (plant shoots and roots) in an NFT could result in total yields exceedig 100 tonnes/ha-yr.

Variations in yield are attributable to a number of factors, including day length, temperature, and length of the growing season. McNaughton (1966) found that cooler temperatures and shorter days promoted rhizome development in Typha and that annual production was greater at low altitudes than at higher elevations.

Periodic harvesting reduces the annual yield of cattail, but less so in artificial systems than in natural marshes (Spangler et al., 1976a; Spangler et al., 1976b). Cordgrass grown in a marsh receiving treated municipal wastewater showed 13 to 41 percent greater biomass than when grown in a marsh not receiving wastewater; decomposition of litter was more rapid in the enriched marsh than in the natural marsh (0.4 and 0.2 percent per day, respectively) (Marshall, 1970).

C.5.b Release of Organic Carbon by Emergents--

Wetzel and Manny (1972) found 0.05 to 25% of the photosythetic carbon fixed was excreted by a submerged aquatic, Najas flexilis, while a much lower percentage was released by the floating macrophyte, Lemna perpusilla. It is likely that low rates of release of organic carbon occur in emergent species because a large proportion of the photosynthate is contained in thick cellulosic cell walls; this tissue is present in much lower quantities in submerged species which can consequently "leak" more dissolved organic compounds. Wetzel (1969) found that organic compounds released by macrophytes are taken up quickly by periphyton (sessile algae and bacteria). Of course, leakage of organic matter in a water treatment system would be of prime concern.

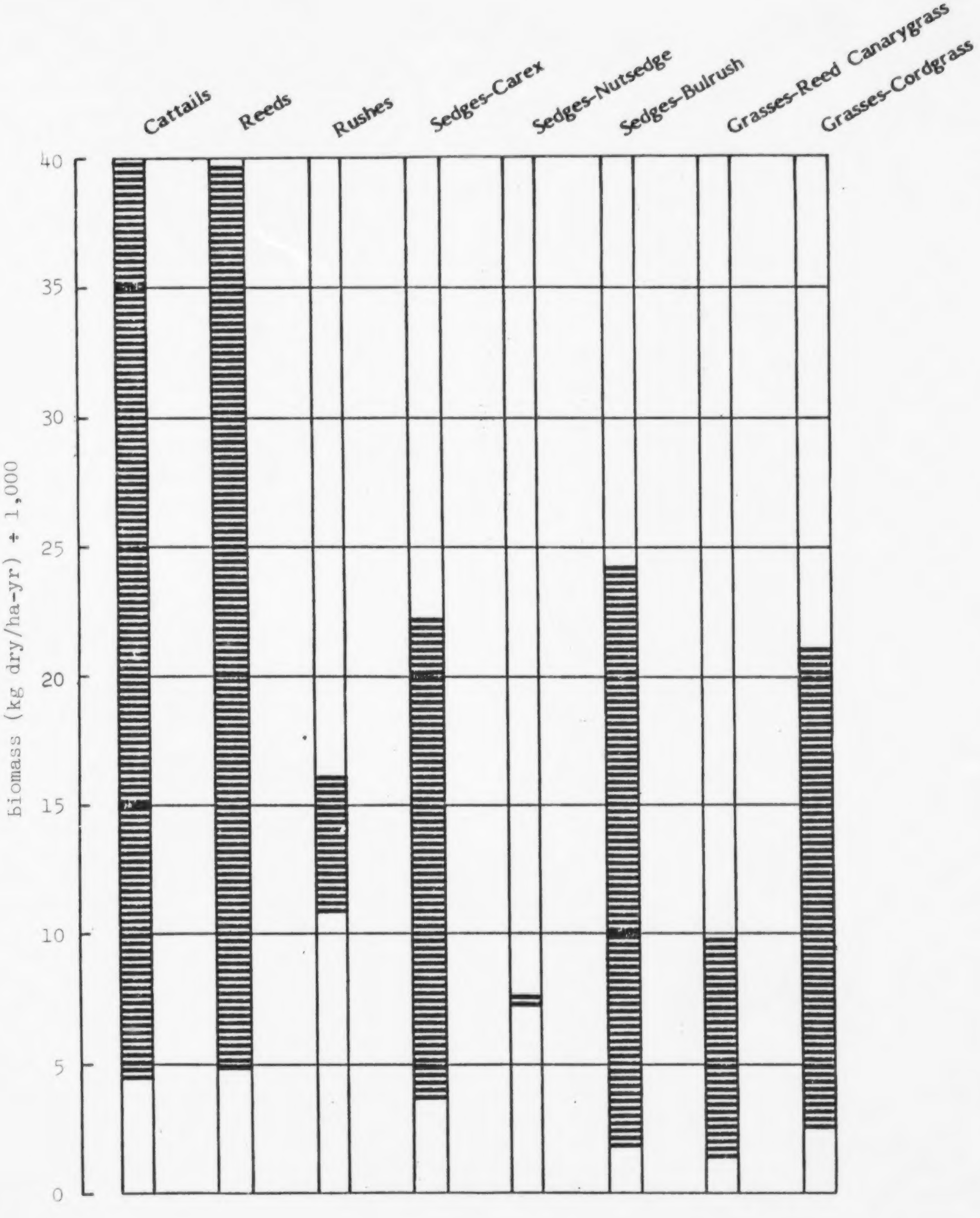


Figure 4.6. Peak aboveground biomass of emergent aquatic plants in natural habitats. (Stephenson et al., 1980)

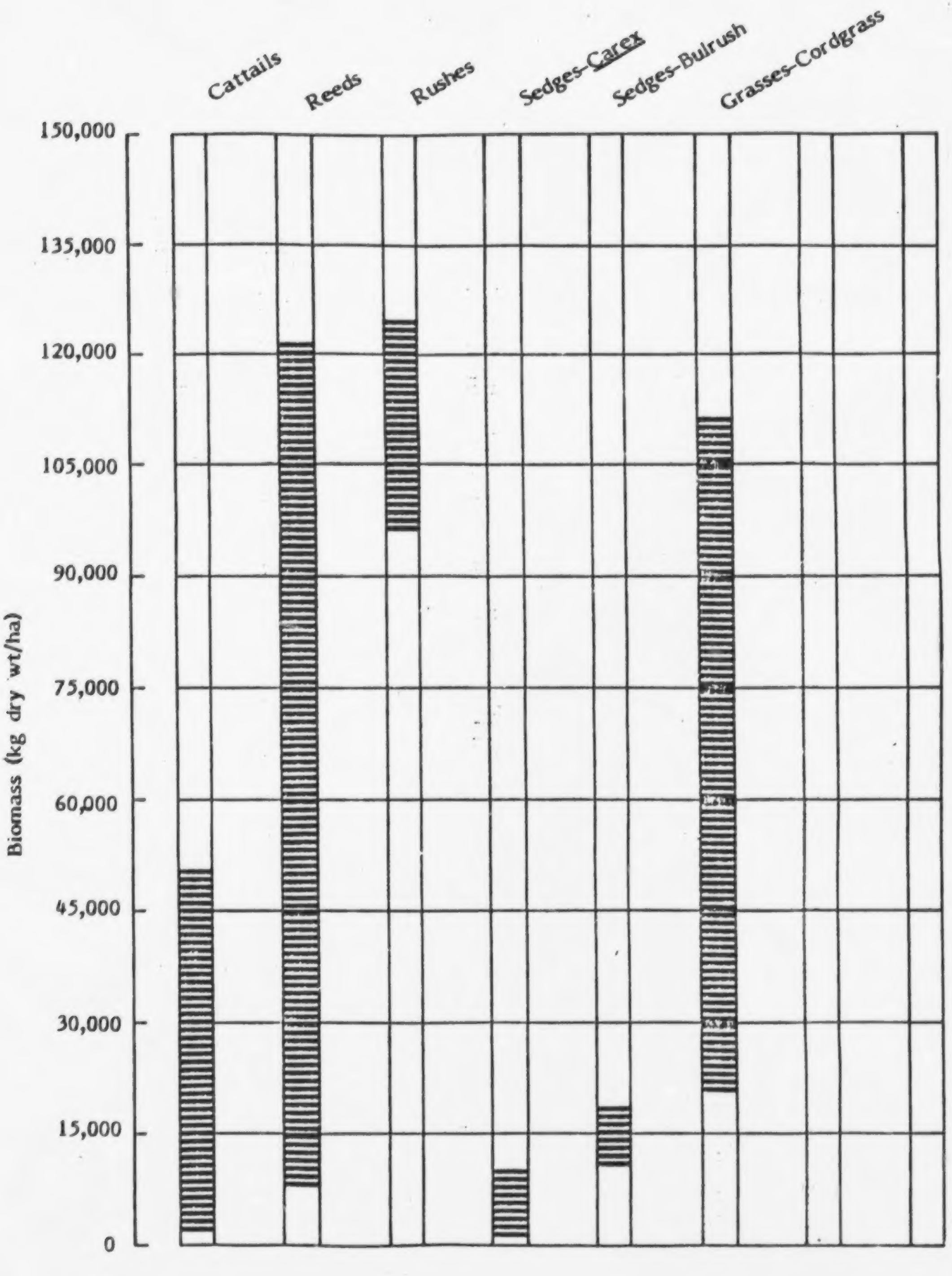


Figure 4.7. Peak belowground biomass of emergent aquatic plants in natural habitats (Stephenson et al., 1980).

C.5.c Life Histories--

In studies with Phragmites communis, Haslam (1973) considered plants with ca. 10 cm shoots to be "established." Each successive shoot produced from the rhizome is generally taller and from a longer rhizome section than the one previous; thus, a 10-shoot plant is usually over 30 cm high, enabling it to survive about 20 cm of flooding. The rhizome can survive a certain amount of drought, with enough reserves to tolerate some grazing or cutting. Depending on environmental factors, seedlings may take from three months to three years to reach this 10-shoot stage, before which mortality is high; for this reason the plant is more easily established on rich sediments than on nutrient-poor media.

Propagation is readily achieved by placing rhizome sections in a moist soil environment. Dykyjova et al. (1971) reported that seedlings require two or three years growth before producing mature, flowering shoots. A three-year-old clone of the plant occupies an area of about 4 m in diameter and is capable of spreading 1 m/yr in each direction. Density of natural stands is usually about 100 to 200 shoots/m^2; shoots may arise from rhizomes of all ages.

The life history of the common cattail (Typha latifolia) is reviewed by Yeo (1964). Generally, cattails are found in wetlands throughout North America. They grow better in fresh water but can tolerate moderately salty water and grow well when water depths range from ground level to 0.5 meter above ground level.

C.5.d Effects of Harvesting on Yield and Chemical Composition--

Corns (1974) showed that for Carex atherodes, increased frequency of harvesting resulted in a lower annual yield (plots harvested six times per year yielded only 40% of the biomass as those harvested twice annually); however, total protein produced annually in plots harvested six times per year was nearly 84% that of plots harvested two times per year. Van der Valk and Davis (1978) found that removal of litter from a Carex stand increased density four-fold.

Reed canary grass yield was not affected by frequency of harvest, but protein content was (Asay et al., 1968). Clipping height was found to be a factor in regrowth of this species; yield was greatest when the grass was clipped to 10 or 11 cm heights (Davis, 1960). Differences in forage quality (lignin and nitrogen content) were found not to be affected by height at harvest in that study. Lawrence and Ashford (1969), however, obtained highest yields from reed canary grass and two other forage grasses when they were cut at 3.8 cm height during the seed stage of development. Persistence of the grasses was low at this cutting height.

C.5.e Regeneration and Reproduction--

Yeo (1964) showed that female spikes of Typha latifolia produced over 222,000 seeds, but that germination was relatively poor unless the cells along the transverse edge of the seed were damaged by pressure (in which case 100 percent germination occurred). One *Typha* seedling matured to cover an area about 3 m in diameter, with 98 aerial shoots and 104 lateral buds, within one growing season.

Phragmites australis spreads mainly by rhizome growth; it generally exhibits poor seed germination and high seedling mortality in the field (Haslam, 1971). Haslam (1970b) showed that a young clone established by a seed or rhizome can advance up to 2 m per year and produce up to about 200 shoots per m^2 in this advancing zone. Stands of *Phragmites* were reported to be harvested regularly once a year in the Danube delta without harm to the plants (Rudescu *et al*., 1965).

C.6 Metabolic Activity of Bacteria on Roots

Seasonal changes in microbial populations of a *Phragmites* stand were found to be related to concentrations of dissolved organic nitrogen and ammonia nitrogen (Ulehlova *et al*., 1973). A small microbial increase in May was followed by a second, more significant increase in late June; the concurrent decreases in dissolved organic nitrogen and ammonia nitrogen suggested that these compounds supplied a portion of the bacterial requirements for nitrogen. Dissolved organic nitrogen concentrations were fairly high throughout the study period, however.

Inorganic nitrogen was present in extremely low concentrations in April and May, reflecting high rates of uptake by algae and macrophytes. Nitrite concentrations in the vegetated areas were considerably lower than in open water areas throughout the growing season. Nitrate concentrations increased considerably during late June and increased slowly thereafter. Ammonia nitrogen concentrations showed the greatest changes during the growing season. Maximum concentrations in August reflected the high rates of decomposition (ammonification) taking place at that time.

CHAPTER V

SCOPE AND METHODOLOGY

The activities reported here describe a three-year + feasibility project of a unique hydroponic wastewater treatment system. The efforts in the first six months, referred to as Phase 0, were designed to test the original hypothesized system at a significant scale to identify the potential of the system as well as the major limitations. A subsequent fifteen-month period, referred to as Phase 1, included further experiments to determine the feasibility of this plant based aquatic treatment system. This was a cooperative effort of several groups and sponsors. The objectives, participating groups and research activities are described below.

A. PARTICIPANTS IN THE PROJECT

In Phase 0, three pilot scale experimental systems were constructed. These systems were used to define major controlling variables that assist in defining plant response to various levels of pollutants in the NFT system. General Electric Company tested the NFT with a well defined inorganic plant fertilizer and water solution in a total controlled environment greenhouse with artificial lighting. Cornell University operated with a similar plant nutrient solution which was modified to simulate a primary settled domestic sewage. A primary settled domestic wastewater was used in the CRREL greenhouse.

In Phase 1, studies at Cornell and in New Hampshire were continued in the Phase 0 mode. Cornell assumed responsibility for plant culturing work which was vacated by General Electric. The NFT project at Cornell was expanded to include two, and at times, three, greenhouses at the Ithaca campus. The original greenhouse continued operation with the synthetic wastewater solution, while the second and third were used for multispecies plant response studies and plant propagation. CRREL continued sewage testing in its greenhouse. In addition, a large greenhouse was constructed at the Hanover, New Hampshire, treatment plant to house larger pilot scale and plant testing. Some sample analyses of the pilot scale unit were conducted by CRREL personnel while plant culturing in sewage work was done by Cornell.

B. METHODS TO MEET THE PROJECT'S OBJECTIVES

The overall goal of the project was to define a cost-competitive and efficient treatment system using the nutrient film technique (NFT). Toward this end were the following objectives:

1. identify and characterize plants capable of performing sewage treatment;

2. establish systems in which these plants can remove pollutants efficiently;

3. characterize the performance of these systems;

4. develop design criteria for larger systems.

To meet these objectives, two basic methodologies were used. First, plant response to the NFT system itself was tested using a well-defined inorganic plant nutrient and tap water substrate. Second, pilot scale NFT units were constructed to test sewage treatment using real or synthetic sewage. Throughout the course of experimentation, many different plants and system configurations were evaluated to get the best estimates of plant and system performance. Plants ranged from wetland and aquatic plants to forages and tropical plants, and eventually to ornamental and horticultural plants. Pilot scale systems ranged from 12.2 to 36.6 m (40 to 120 feet) in length and treated between 0.47 and 11.36 m^3 (125 and 3000 gallons) per day. A chronology of the major research activities is summarized in Figure 5.1.

C. PHASE 0 ACTIVITIES

C.1 Cornell University

The tasks of the Cornell University team for Phase 0 were to estimate organic and nutrient removals by the NFT system and examine the kinetic effects of increasing loading rates on the NFT system. During Phase 0, the daily application rate was 10 cm (4 inches) per day, and this daily rate was not increased. However, data were collected from intermittent loading cycles. These included loadings of four to eight times the instantaneous flow rate of continuous application, and included long periods of draining to promote root zone aeration.

Studies at Cornell were conducted with a synthetic wastewater feed equivalent to a medium strength domestic primary sewage. This substrate also contained a known level of cadmium for study of the fate of an important heavy metal in the NFT system. This portion of the work was conducted in parallel with studies on domestic sewage conducted in New Hampshire.

This work at Cornell resulted in development and testing of original designs for NFT facilities, including trays for plant growth, dosing systems, sampling stations and management procedures for maintenance of these facilities. The Cornell pilot scale unit developed in Phase 0 is shown in Figure 5.2, along with those developed and tested at GE and in New Hampshire. Experience was gained in propagation of reed canary grass which was used in all Phase 0 work at Cornell and CRREL. Data were collected for over three months on organic removals, nutrient transformations, heavy metal uptake, plant yield, oxygen relationships and environmental conditions.

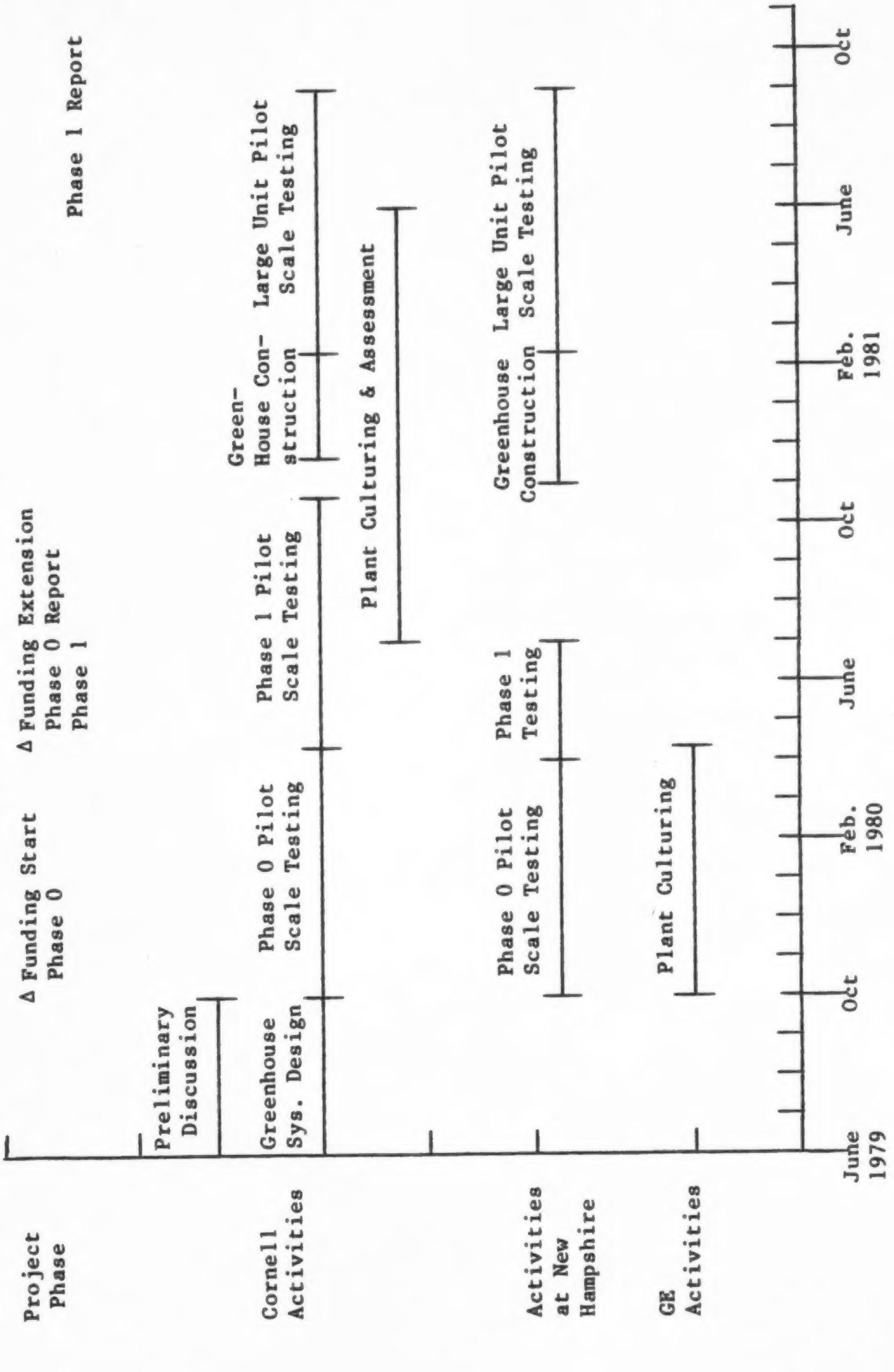


Figure 5.1. Chronology of major events and testing periods of the NFT project.

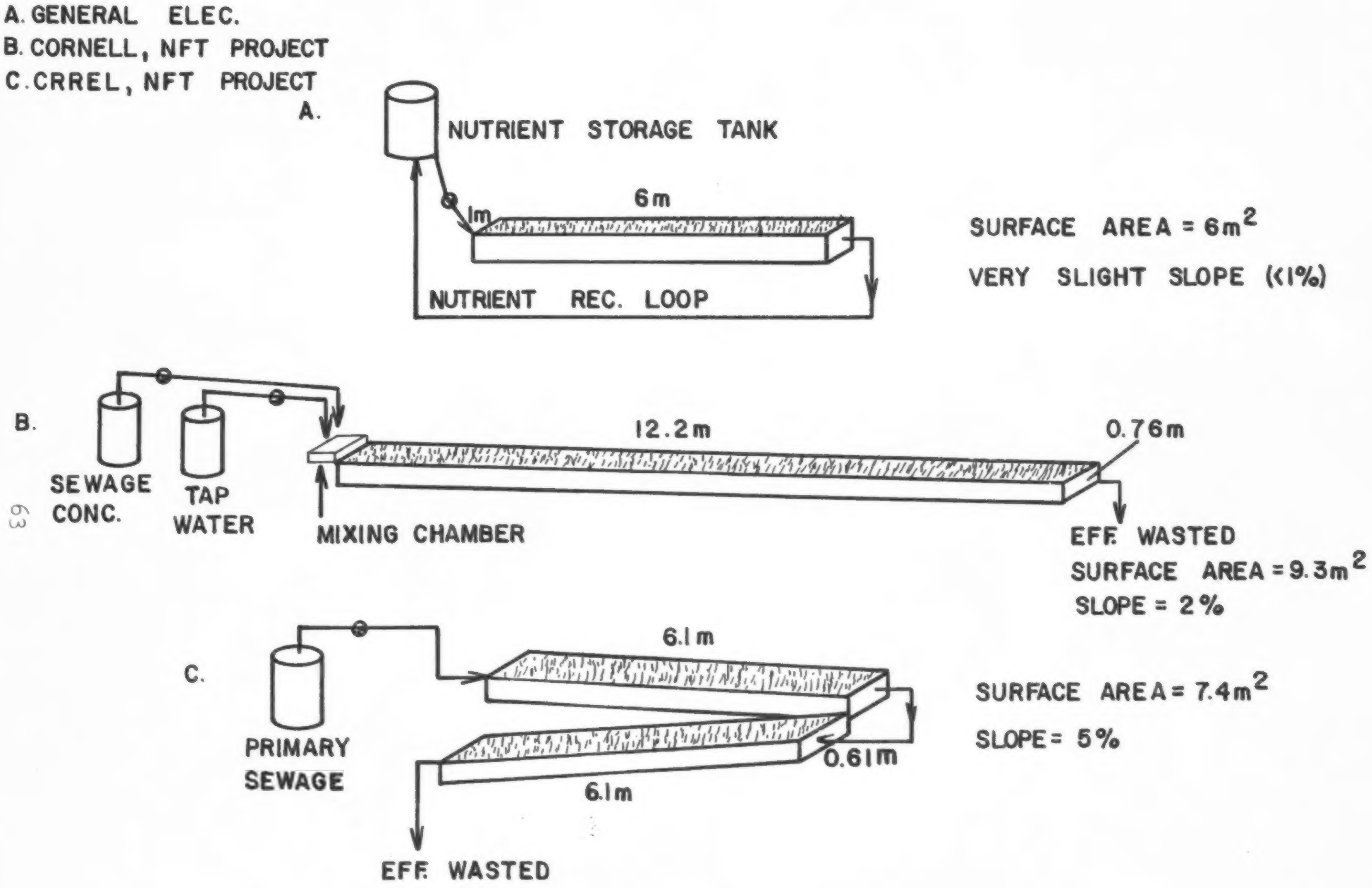


Figure 5.2. Different NFT systems at Cornell University, General Electric Company Syracuse facility, and at CRREL in Hanover, New Hampshire.

C.2 New Hampshire

In Phase 0 the main task of the New Hampshire unit operated in the CRREL greenhouse was to determine the response of reed canary grass to domestic sewage. Tests were similar to those performed at Cornell. A range of flow rates was used, with all flows being intermittently applied. Again, reed canary grass was the test species. The analyses performed on the wastewater included gross organic and nutrient determinations as well as yield, hydraulic retention time, and environmental conditions.

C.3 General Electric

The principal task of the General Electric Controlled Environment Agriculture Operation (CEAO) was that of defining cultural methods and nutrient responses. The unique characteristic addressed was the presence of relatively low levels of nutrients. Five plant species were tested for their adaptability and assimilation. These included reed canary grass, coastal bermuda grass, napier grass, watercress and cattails. Sufficient quantities of these were propagated to estimate nutrient uptake, transpiration rate and biomass production. Unlike the Cornell and CRREL "one pass" systems, which were designed to monitor mass and concentration changes, the solution depth and flow rate were not critical in the GE recirculated systems. Due to the highly synthetic nature of this portion of the study, no data will be reported in this final report on this phase of the study.

D. PHASE 1 ACTIVITIES

D.1 Cornell University

Testing continued on the canary grass units similar to testing done in Phase 0 at Cornell in Phase 1, but the range of loading rates was increased up to a peak of 40 cm (16 inches) per day. Canary grass units were joined end to end to test the effect of longer units, and grass was transplanted into the units and harvested. Since this phase of the project included spring and summer months, testing the units under more favorable light and temperature conditions than in Phase 0 was possible.

In addition the Cornell team assumed the plant culturing responsibilities vacated by General Electric after Phase 0. Many potentially suitable plant species were identified and either grown from seeds or stock, or collected in various forms from the field. These plants were tested for their adaptability and productivity in small NFT systems. Many of them were tested in carbon free solution to determine their nutrient uptake rates. Some plants were also tested in recirculating sewage systems to assess their uptake rates under organic loadings. A wide variety of plants was grown in the one-pass sewage system in the Hanover greenhouse. These growth trials allowed conclusions to be made concerning plant suitability and performance, and identified management techniques necessary for operating a large system.

A large (120 foot) multispecies unit was tested extensively at four distinct loading conditions, ranging from 6.9 cm to 40 cm (2.7 to 16 inches) per day, using the synthetic sewage. The different regions of this system represented the various parts of the hypothesized NFT treatment system--roughing filter, nutrient stripping and polishing steps. These experiments were paralleled using domestic sewage at the Hanover treatment plant.

Smaller scale experiments were undertaken in two areas: first, performing a closer examination of the root zone to assess the effects of root surface, water depth and associated growth around the roots, and second, to design a system to perform significant organic and solids removal in a small area. This second activity used trays that could contain up to 12 inches of wastewater which were periodically flooded and emptied. This activity was carried out at the Village of Cayuga Heights (New York) sewage treatment plant in the town of Ithaca, New York.

D.2 CRREL

At the start of Phase 1, CRREL continued testing the pilot scale reed canary grass unit with sewage. Several additional loading conditions were tested. Along with the Cornell team, CRREL personnel set up and operated the greenhouse at the Hanover treatment plant, which tested loading rates from 5 to 20 cm (2 to 8 inches) per day. Extensive analyses, similar to those run at Cornell, were completed in the CRREL laboratories. In addition to other analyses, these units were tested for trace organic removal, with the analysis being conducted by CRREL.

CHAPTER VI

MATERIALS AND METHODS

The goal of this study was to define the conditions that would enable the application of a solar-powered plant system to be used as a water purification system. This broad-scoped feasibility study thus required a wide range of variables to be evaluated--a variety of plants needed to be grown with defined substrate and with "real world" sewage; the scale of the experiments had to be large enough to enable extrapolation to full scale; and experiments had to be long enough to reflect seasonal influences as well as senescence problems when used for several years. Plant systems have been tested for up to three years, flow rates up to 11 m^3/d (3000 gallons per day) have been applied with a synthetic wastewater and sewage enabling comparison of effects of unknown constituents in sewage to a defined situation. NFT units were established in four separate locations in New York and New Hampshire. The definition of the approach is given in this section.

The total time frame for this study was three years, with most of the extensive testing completed in a two-year time space in the middle of the program. The first eight months of this effort were referred to as Phase "0" and were intended to be a confirmation of whether the NFT could be adapted to wastewater treatment. These preliminary tests were followed by more comprehensive testing in a longer period referred to as Phase I.

A. PROCESS DEFINITION WITH SYNTHETIC SEWAGE - STUDIES AT ITHACA, NEW YORK

A.1. Synthetic Sewage Composition

To gain better control of influent variables, the Cornell systems utilized a synthetic medium strength domestic wastewater. A previously developed formula (Switzenbaum and Jewell, 1978) was modified to produce the following theoretical concentrations:

COD	400 mg/ℓ
N	40 mg/ℓ
P	15 mg/ℓ

Sucrose was added as the carbon source. Commercial silage urea was used as the nitrogen source. The carbon added as urea was negligible compared to that added as sucrose. The use of urea-nitrogen enabled estimates to be made of the fate of all forms of nitrogen commonly found in fresh domestic sewage. Phosphate was added as mono- and dibasic potassium phosphates. The presence of both compounds contributed to the buffering capacity of the system, and the use of potassium salts served as a potassium source to the grass. In addition to these constituents, yeast extract was added as a trace element source. To further increase trace nutrients, tap water was used for all solutions. Cadmium sulfate was added to produce a concentration of 0.2 mg/ℓ cadmium (Cd) in the simulated sewage. Some difficulty was experienced in controlling the cadmium concentration.

Dry chemicals were weighed and dissolved into concentrated solutions which were diluted with tap water to produce the wastewater. Chemicals were dissolved in 20 ℓ of tap water, diluted to 100 ℓ in the feed storage tank, and further diluted 15 times in the distribution box. The amounts of dry chemicals dissolved in 20 ℓ of tap water, diluted to 100 ℓ in the feed storage tank and further diluted 15 times in the distribution box. The amounts of dry chemicals dissolved in the 20 ℓ concentrate are shown in Table 6.1.

TABLE 6.1. DRY CHEMICAL CONSTITUENTS IN CONCENTRATED FEED STOCK AND SYNTHETIC SEWAGE

Constituent	Stock Concentration g/20 ℓ	Sewage Concentration mg/ ℓ	Major Constituents mg/ ℓ
Sucrose	536	357	COD-400
Yeast Extract	3	2	---
Urea	130.5	87	N-40
KH_2PO_4	75	50	P-11
K_2HPO_4	30	20	P-4
$CdSO_4$	0.686	0.46	Cd-0.2

Total feed concentrate storage volume was 200 ℓ. This provided more than three days' storage time at the given withdrawal rates. This time period was long enough to minimize labor in feeding the system, while being short enough to minimize problems of changes in feed composition due to microbial activity and/or chemical hydrolysis.

The initial formulations of the feed mixture also included sodium bicarbonate as a buffer. However, the addition of this constituent resulted in the formation of an inorganic precipitate in the distribution box and among the grass roots. Its formation was particularly noticeable under warm conditions. Due to this precipitate and the lack of an apparent need to further buffer the system, this constituent was deleted from the formula.

At the start of the testing program, the wastewater was added continuously at a rate of 655 mℓ/minute, which corresponded to a loading of 10 cm/day. This flow was made up of 611 mℓ/minute of tap water and 44 mℓ/minute of feed stock. In subsequent intermittent applications, the total application time was six or three hours per day. Additional information on loading schedules is given later. Since the total application remained 10 cm/day, the flows during the application periods were 2650 and 5300 mℓ/minute, respectively. The mixing ratio of tap water to feed concentrate of 14:1 remained the same. All subsequent loading conditions used some variation of a feed concentrate—tap water mixture.

The concentration of the stock concentrate solution could be increased up to eight times without precipitating some constituents. This allowed increased loading rates up to 81 cm/day without an increase in the feed storage volume or feed makeup frequency. Rather, the mixing ratio in the distribution box was increased. This also provided flexibility in application rates and feed storage periods. At high loading rates, it was necessary to increase the feed pump rate and prepare feed concentrate more frequently.

For the purposes of maintaining seeded and sodded control systems, a solution of Peter's brand soluble fertilizers was used in recirculating systems. A mixture of Peter's Hydrosol (mixed nutrient) and $Ca(NO_3)_2$ fertilizers maintained adequate levels of N, P and K. Sequestrene chelated Fe III was added periodically to reduce iron deficiency in the grass. During periods of high light intensity or low foliar cover, algae buildup raised pH values. This was controlled and/or corrected by additions of copper sulfate or nitric acid. These additions occurred only in the background phase of work, and all of the data were taken from units which were not being treated for algal growth. As will be discussed, algae growth is a major problem in propagation and start-up.

In operating the 1.5 meter (5 foot) bench scale unit in Ken Post labs, the feed solution was modified. The unit used 7.5 ℓ reservoirs, and the solution was recirculated, so only a small amount of synthetic wastewater was needed at the start of each experimental run. The following amounts of chemicals were dissolved in the 7.5 ℓ reservoirs to produce identical concentrations to the synthetic wastwater:

NH_4Cl	1.148 g
K_2HPO_4	0.33 g
KH_2PO_4	0.21 g
Yeast	0.75 g
Sucrose	1.379 g

The carbon source sucrose was added in only those experimental runs where removals of BOD, COD, and solids were of interest. Since very small amounts of Cadmium (Cd) would have been difficult to add, 10 mℓ of a stock $CdSO_4$ solution were added to produce the correct concentration.

An additional experiment with the 1.5 meter (5 foot) bench scale unit evaluated BOD removal at various loading rates using reed canary grass and required a one-pass through flow of wastewater. A 627 ℓ (165 gal.) reservoir of synthetic wastewater was a common source of feed for each of the six troughs on the unit. The following amounts of dry chemicals were dissolved in the reservoir:

Urea	54.9	g
K_2HPO_4	12.6	g
KH_2PO_4	31.5	g
Yeast	1.2	g
Sucrose	130.7	g
$3\ CdSO_4 - 8H_2O$	0.285	g

A.2. Pilot Scale Units (Bracehouse)

A.2.a. Brace greenhouse and test units--

The NFT work at Cornell is being conducted in an asymmetrical greenhouse with a large, inflated polyethylene south wall and a smaller, opaque, insulated north wall. This greenhouse is designed to maximize solar energy input and conservation in colder climates and is patterned after the original design of this type developed at the Brace Institute (Laward *et al.*, 1975). The Cornell Brace-style greenhouse is illustrated in Figure 6.1. (Albright *et al.*, 1978).

The greenhouse has floor dimensions of 7.3 x 14.6 meters (24 x 48 feet), and contains four benches, each 0.76 x 12.2 meters (2.5 x 40 feet). The north wall is shingled, contains 14 centimeters (5 1/2 inches) of fiberglass batting, and is lined on the inside with white polyethylene to enhance light reflection to the benches. The roof peak is 4.6 meters (15 feet) from the floor, and the south wall angle is 38°. Two 27 megajoule (7.5 kw) heaters at floor level provide enough supplemental heating to maintain a night temperature of about 12°C (54°F) under winter conditions. An automatic ventilation system maintained the temperature below 35°C.

A third greenhouse was used for a short period for plant growth and storage. In a joint project, the departments of Agricultural Engineering and Floriculture and Ornamental Horticulture built a 12.2 x 30.5 meter (40 x 100 foot) air-supported, cable-restrained greenhouse. The covering material was a double layer of Loretex woven polyethylene with ultraviolet stabilizers. Although the air-supported nature of the greenhouse required four air changes per hour, the temperature range was maintained between 15.6 and 23.9°C (60 and 75°F).

Work begun in the Cornell greenhouse on June 4, 1979, was geared toward gaining experience with establishment of reed canary grass in the hydroponic (NFT) units. Both transplanted sod and grass germinated from seed were investigated to determine the most efficient means of establishment so that testing could begin within the time constraints of the project. Results of this work, which resulted in the use of transplanted sod rather than seeded grass, are discussed in more detail in a later section.

Also developed during this phase of work were NFT trays to contain grass and distribute the nutrient film flow, distribution boxes to mix and distribute influent to the NFT units, storage and pumping systems to feed the

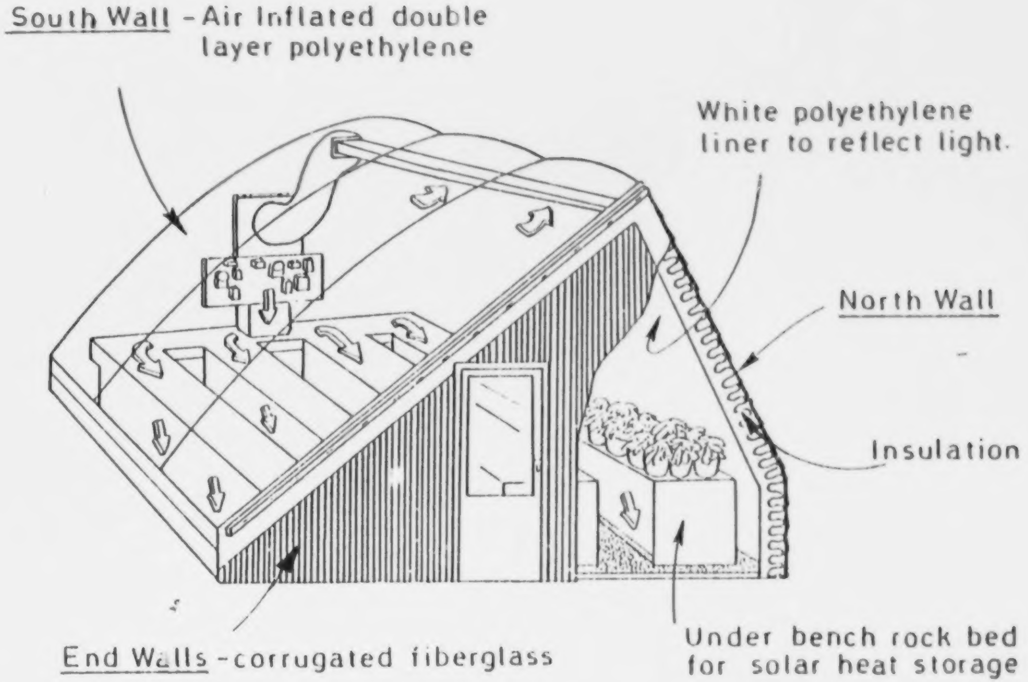

South Wall - Air Inflated double layer polyethylene
White polyethylene liner to reflect light.
North Wall
Insulation
End Walls - corrugated fiberglass
Under bench rock bed for solar heat storage

Figure 6.1. The Cornell Brace-style solar greenhouse.

units, and procedures for routine maintenance of the facility. During the latter part of the summer, after grass establishment, regular harvests were made of the foliar production by hand-clipping the foliage to a level of four inches above the roots. Records of the fresh and dry matter yields were kept and are reported in the Results section of this report.

Beginning work about four months in advance of project funding enabled the Cornell group to establish a facility with a mature crop ready for testing at the beginning of the project. This background work assumes more importance when it is realized that none of the equipment or procedures were packaged or ready-made but had to be designed to fit the existing facilities. Through trial and error, the experimental setup evolved from the initial designs so that it has performed with very little maintenance and has been readily adapted to different operating conditions during the test phase of the project.

The following sections describe various parts of the NFT system in operation at Cornell. This experimental setup is shown in Figure 6.2.

The general concept of the NFT units is a system of 10 trays in series with the provision for recycling flow to a holding tank or direct disposal of effluent. The trays have a 2 percent slope. The Cornell units conform to this schematic plan except that they are 0.76 m x 1.22 m (2.5 x 4.0 ft) [9.3 m^2 (100 ft^2) surface area] due to space limitations in the greenhouse.

A design incorporating 10 trays, each 1.2 m (4 ft) long x 0.76 m (2.5 ft) wide and made of wood and plywood, was produced. Between each successive tray section was a two inch drop to the next tray, providing aeration of the wastewater in these cascades. These were built beginning in June 1979. The standard tray is shown in Figure 6.3. Trays were lined with polyethylene and overlapped to form the unit. Supports consist of wooden blocks fitted with threaded rods. These are shown in Figure 6.4, a section view of the tray, which also illustrates the sampling ports.

Sample ports were placed at intermediate points in the unit by drilling through the 5 x 10 cm tray support, cutting a hole in the plastic liner and inserting plastic tubing, flush with the tray floor. Ports were installed at points 3.7 m and 8.5 m from the distribution box, and these are referred to as points A and B, respectively. Two sampling ports were installed at each point. The two-inch drops between trays were removed in 1980 since Phase 0 had shown that little aeration took place in these cascades.

In December 1980 another 12.2 meter (40 foot) unit was disassembled in preparation of building a level unit able to withstand flooding by up to 30 centimeters (12 inches) of synthetic wastewater. Greenhouse benches supporting the original sloped unit were joined end to end; 46 centimeter (18 inch) wide strips of 2 centimeter plywood was added to form sides; and one end wall and a plastic liner were installed to contain the wastewater and plant roots. The completed system is shown in Figure 6.5.

Figure 6.6 is an overview of the interior of the Brace greenouse which gives an overview of the units. The test unit of transplanted reed canary grass

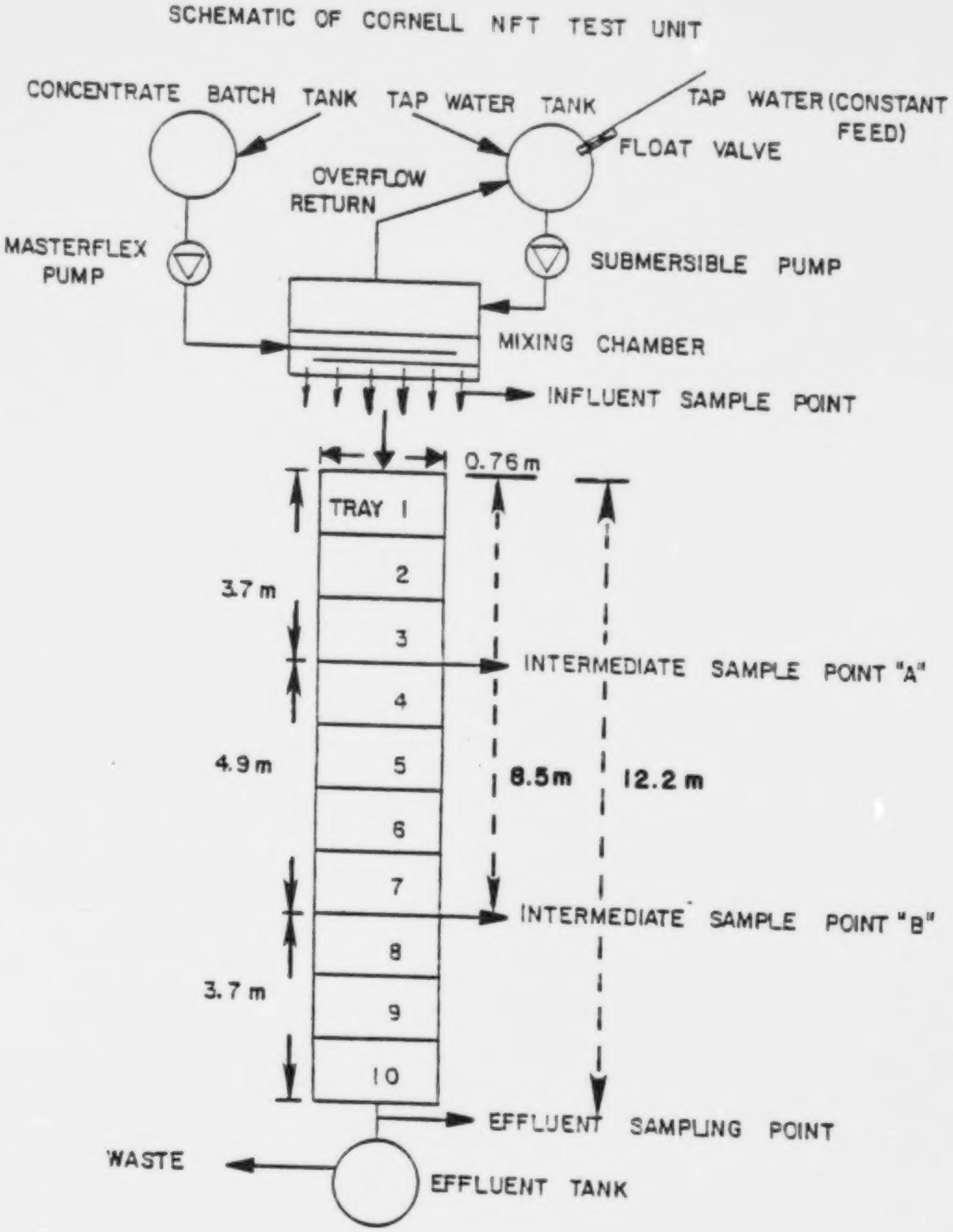


Figure 6.2. Schematic diagram of basic Cornell NFT experimental unit.

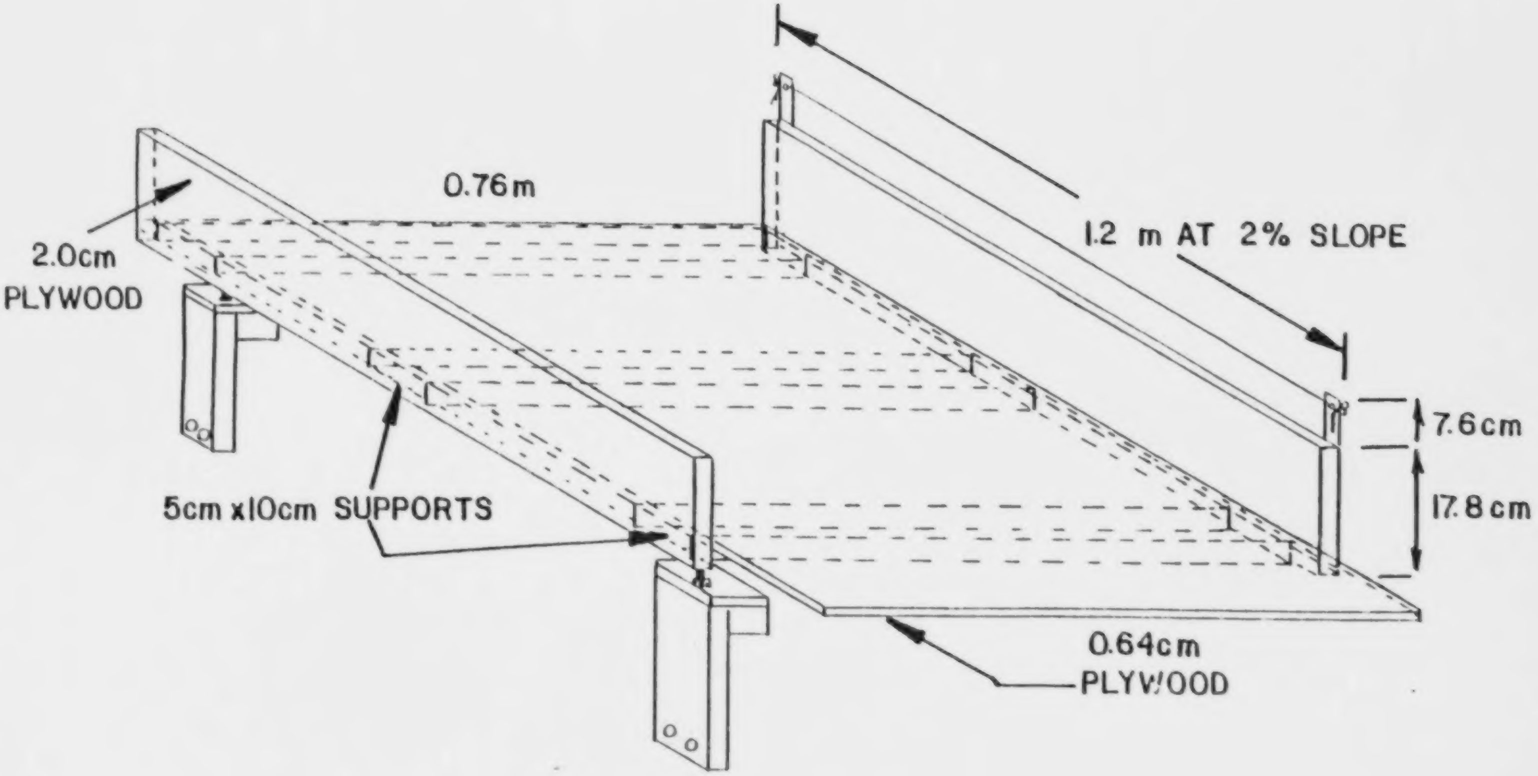


Figure 6.3. Standard NFT tray.

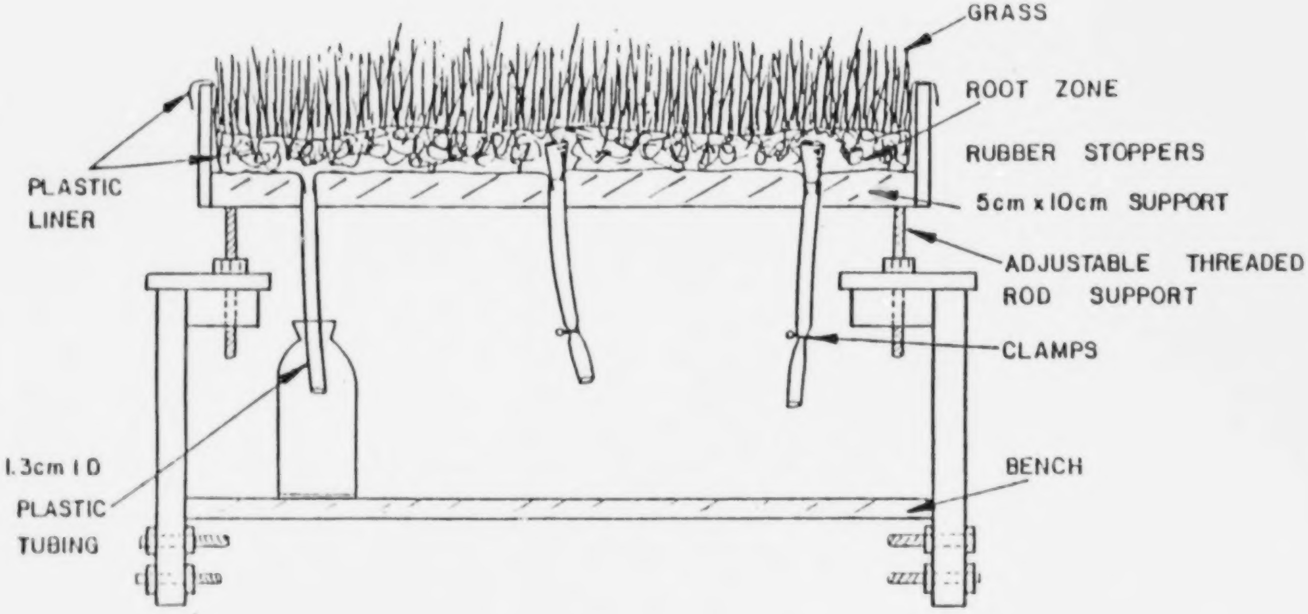


Figure 6.4. Section view of NFT tray, sampling ports, and adjustable support structure.

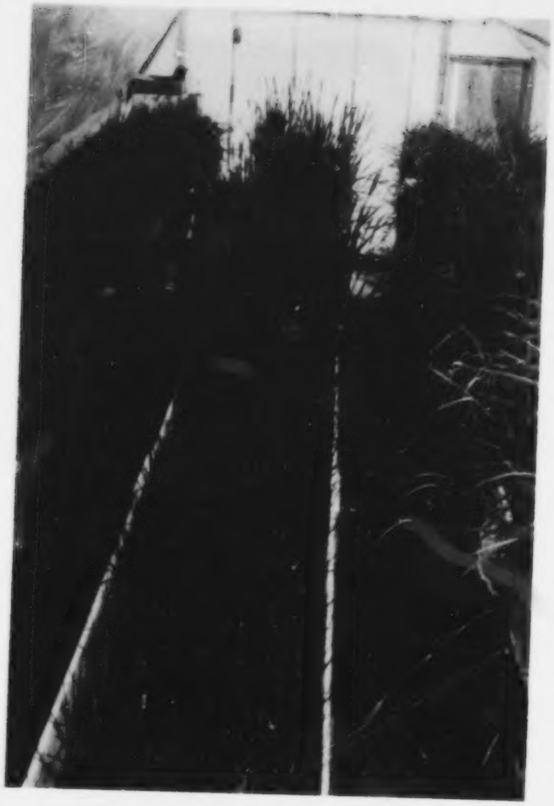


Figure 6.5. Level unit that can withstand flooding.

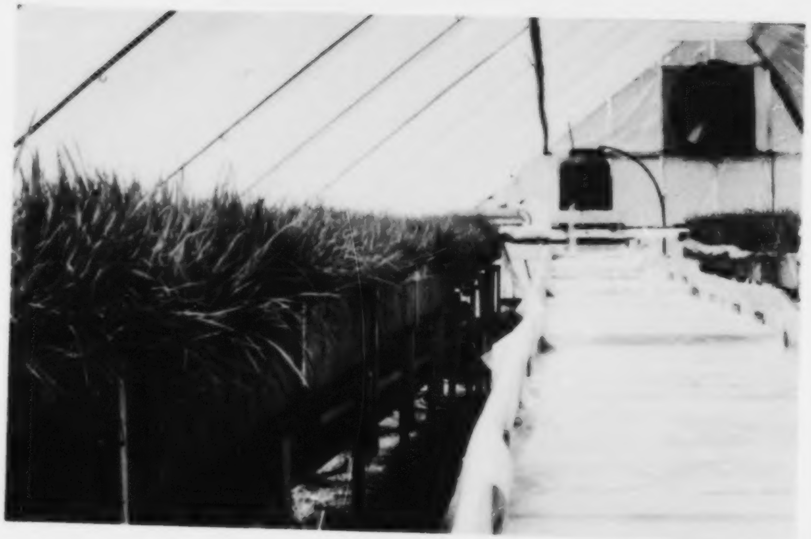


Figure 6.6. View of interior of Cornell solar greenhouse showing NFT trays empty (right) and containing reed canary grass (left).

sod is on the left, while the seeded reed canary grass unit is on the far right. The empty middle unit illustrates the placement of plastic liner in the trays.

Figure 6.6 also shows distribution boxes that were designed to achieve influent mixing. The design of the influent distribution boxes is shown in Figure 6.7.

Tap water supplied by a constant rate submersible pump entered the rear chamber of the distribution box. A portion of this flow passed through a 30° V-notch weir into the front chamber, where the concentrate was introduced and mixed with the tap water. This flow was regulated by a movable flat overflow weir which set the water level in the rear chamber. Overflow recirculated to the influent tap water barrel. The overflow weir level was set manually, and a V-notch discharge weir provided a visual check on flow rate. Figure 6.8 shows the system in operation, discharging to a gravel filter which further distributed flow prior to entering the NFT reactor. The gravel filter was used in this manner until development of a thick root mass of grass rendered it superfluous, at which time it was removed.

In testing conditions where large instantaneous flows were required, distribution boxes were not used because it was difficult to make fine adjustments in large flows. Rather, tap water was sequentially passed through a pressure regulator, solenoid valve and gate valve. The regulator insured the same pressure was delivered to subsequent valves. The solenoid valve, which was activated by cycle timers, controlled the tap water flow during intermittent loading conditions. The gate valve controlled the actual flow rate into the unit. In this setup, feed concentrate was introduced and mixed in the tap water delivery pipe above the gate valve. The feed was delivered from a concentrate solution by a Masterflex positive displacement pump, just as in the distribution box system.

When more than a single 12.2 meter (40 foot) unit was being tested in a sequential system, float-activated submersible pumps placed in catch barrels were used to transfer wastewater from the foot of one unit to the head of the next. During the two highest loading conditions it was necessary to add a pump to the waste line.

Air temperature at bench level was monitored with a recording thermometer (Taylor Instrument Company) which provided a permanent temperature record on seven-day strip charts. The temperature records also provided a very reliable record of sunlight due to an almost instantaneous response in the greenhouse temperature to sunlight above the baseline temperature of 12°C (54°F). Virtually the entire testing period during Phase 0, and a significant portion of Phase 1, coincided with outside air temperature in Ithaca which did not reach 12°C (54°F), so any inside readings above this value were due to sunlight. These data will be examined to determine if any correlations exist between temperature and system performance.

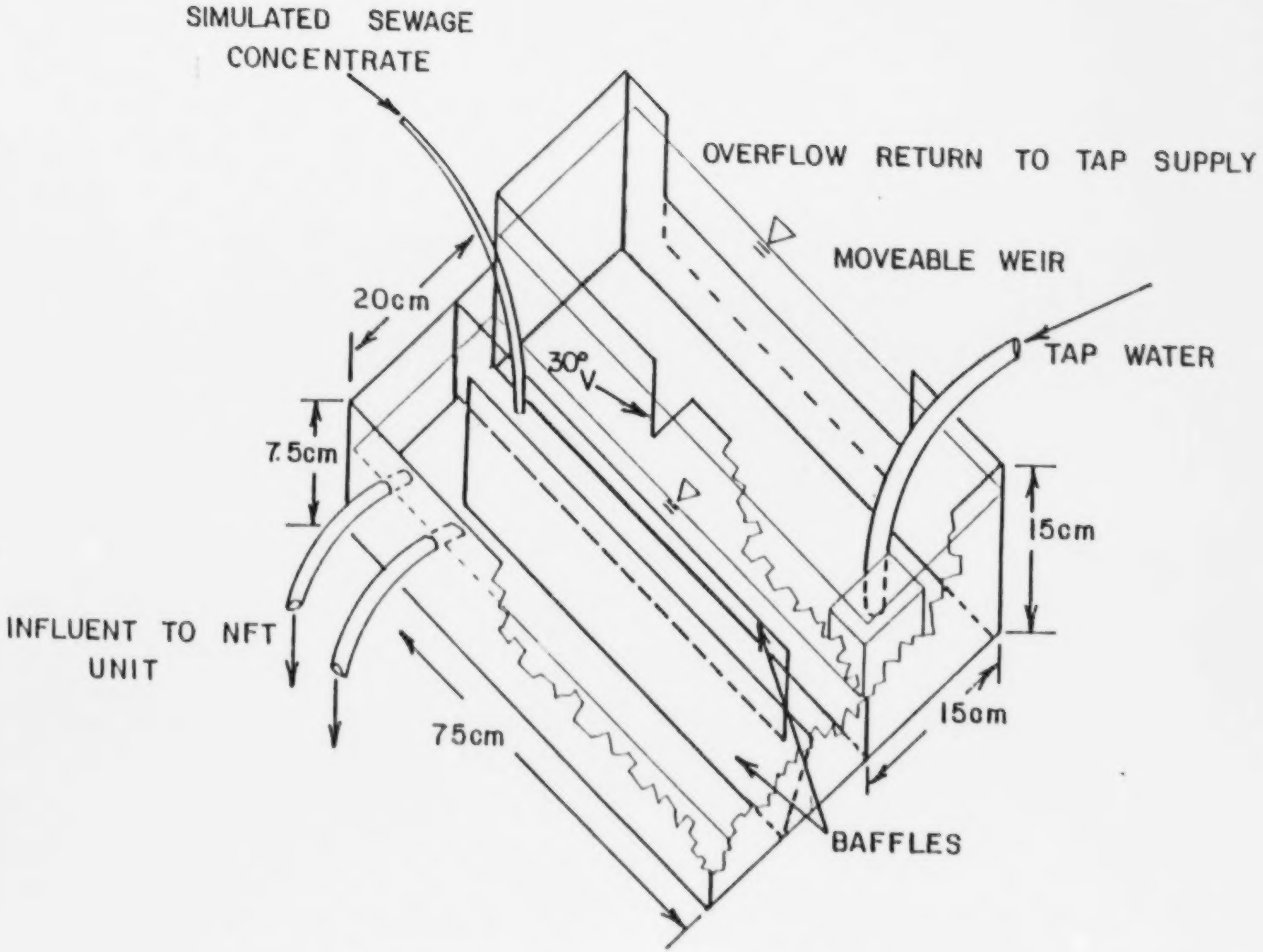


Figure 6.7. Schematic diagram of the influent distribution box.

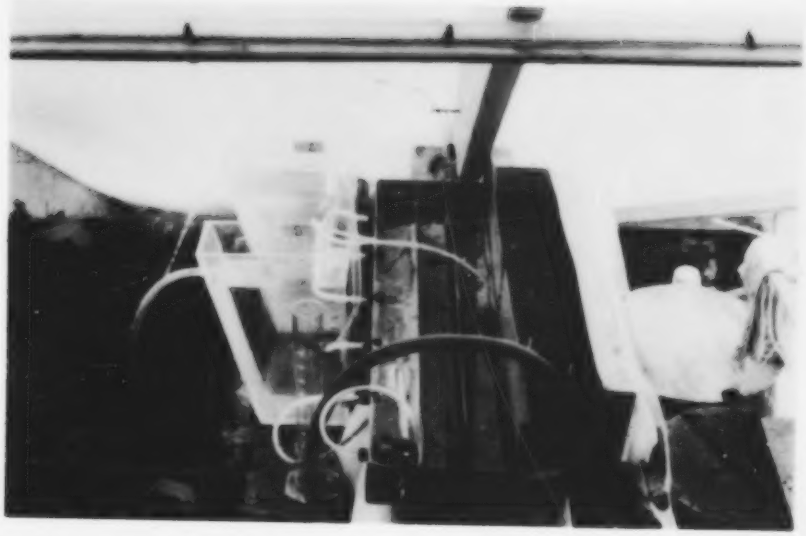


Figure 6.8. View of synthetic wastewater mixing and distribution system.

A.2.b. Loading Rate Schedule and Plant Species Tested--

A variety of loading rates, unit lengths and plant species were tested in the Cornell Brace house. In Phase 0 all testing used 12.2 meter (40 foot) length units containing reed canary grass. These units were loaded at 5 to 20 centimeters (2 to 8 inches) per day (473 to 1890 liters per day), and were operated at a variety of intermittent and continuous conditions. These conditions are summarized in Table 6.2. In Phase 1 these series of experiments continued and more data were collected on individual units. In the summer of 1980 the third and fourth units were interconnected so that the effluent from the third became the influent to the fourth. In this longer system it was hypothesized that most COD removal would occur in the first 12.2 meters (40 feet), which would allow the second to perform as a nutrient removal step. These systems used canary grass only. The schedules of testing with single and double unit systems are shown in Table 6.3. Since the Brace house normally contained four working units, there was space available to perform culturing experiments, retention time tests and biomass comparisons in addition to the major analytical work. While the primary testing units had canary grass derived from field collection of sod, the secondary units were grown from seed. These units provided "clean root" comparisons for retention time studies and growth comparisons for the test units. Grass grown from seed in these units was eventually used in the 36.6 meter (120 foot) pilot units at Cornell and Hanover.

TABLE 6.2. PHASE 0 TESTING SCHEDULE FOR THE BRACE HOUSE 12.2 METER (40 FOOT) CANARY GRASS UNIT. LOADING RATE OVER THE TESTING PERIOD WAS 10 CENTIMETERS (4 INCHES) PER DAY, OR 1.24 $m^3/m\text{-}d$ (946 LITERS PER DAY)

Condition Starting Date	Wastewater Application Mode	Instantaneous Flow During Application (ℓ/min)
12- 6-79	Continuous application	0.66
1- 3-80	30 minute loading, 90 minute pause, Alternating cycle.	2.62
1-28-80	15 minute loading, 105 minute pause, Alternating cycle	5.24
2-21-80	30 minute loading, 90 minute pause, Alternating cycle.	2.62

TABLE 6.3. PHASE 1 SCHEDULE FOR THE BRACE HOUSE 12.2 METER (40 FOOT) AND 24.4 METER (80 FOOT) CANARY GRASS UNITS

Date	Unit Number	Daily Loading cm/day	Daily Loading m^3/m-d	Liters per Day	Application Mode or System Setup
3-18-80	4	5	0.62	473	Continuous application
5-12-80	4	10	1.24	946	Continuous application
6-17-80	3	5	0.62	473	Continuous application
7- 4-80	3	20	2.49	1890	Continuous application
9- 9-80	3+4	10	2.49	1890	Effluent of 3 used as influent to 4
10-16-80	3+4	20	4.98	3785	Effluent of 3 used as influent to 4

In the fall of 1980 the greenhouse units were rebuilt to contain a system of three 12.2 meter (40 foot) lengths connected in series, with each unit containing a separate plant species. The rationale for this arrangement was to use the capabilities of different plants to the best advantage. The three sequential units specialized in acting as a roughing filter for gross organics, a nutrient removal step and a polishing step, respectively; and each contained a species suitable to the task. The first unit was built level so that the water level could be raised, held and lowered on an intermittent flooding regime. In fact the unit never operated in that mode, but the level unit did provide for a larger volume of water in that unit and thus a longer retention time.

The original selection of plants for this large system included phragmites, cucumbers and canary grass for the roughing, nutrient uptake and polishing steps, respectively. The three part system at Hanover, which was identical to that at Cornell, is shown in Figure 6.9. After testing the first condition of 6.9 centimeters (2.7 inches) per day (1893 liters per day), it became obvious that phragmites and cucumbers were not suitable for location in the roughing section. Phragmites showed poor growth and a large buildup of black material around the roots while cucumbers did not develop a large root mat and plants did not appear vigorous. For the duration of the pilot scale studies the first unit was loaded with 6.1 meters of cattails followed by 6.1 meters of bulrush, and phragmites were placed in the second 12.2 meters. The third 12.2 meter unit contained canary grass. A schematic diagram of this arrangement is shown in Figure 6.10. The loading condition regime proceeded to test 10.2, 20.3 and 40.6 centimeters (4, 8 and 16 inches) per day (2839, 5678 and 11356 liters per day) before returning to repeat the 6.9 centimeters per day loading. The testing schedule for this system is shown in Table 6.4.

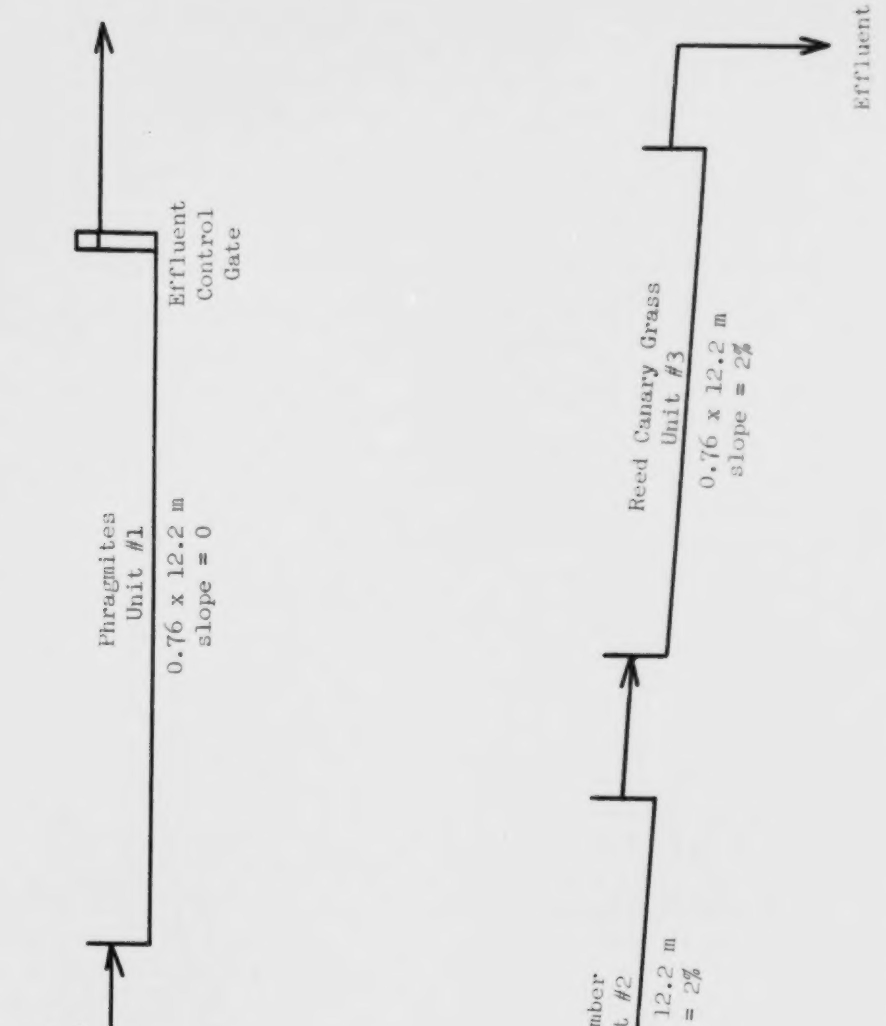


Figure 6.9. Schematic diagram of three-part 36.6 meter system at Hanover containing several species.

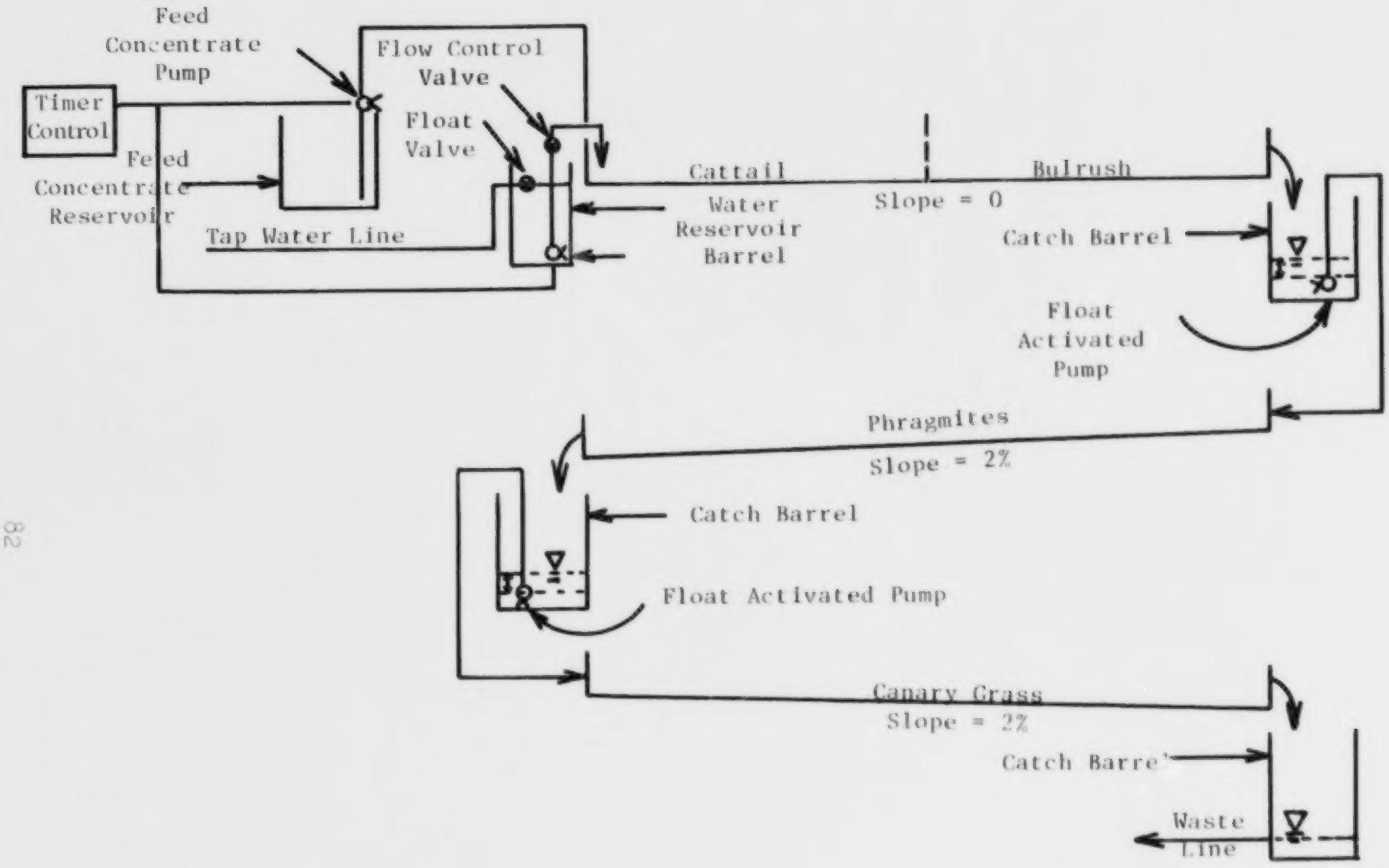


Figure 6.10. Schematic diagram of Bracehouse 36.6 meter multispecies unit.

TABLE 6.4. TESTING SCHEDULE FOR THE CORNELL 36.6 METER (120 FOOT) MULTISPECIES SYSTEM

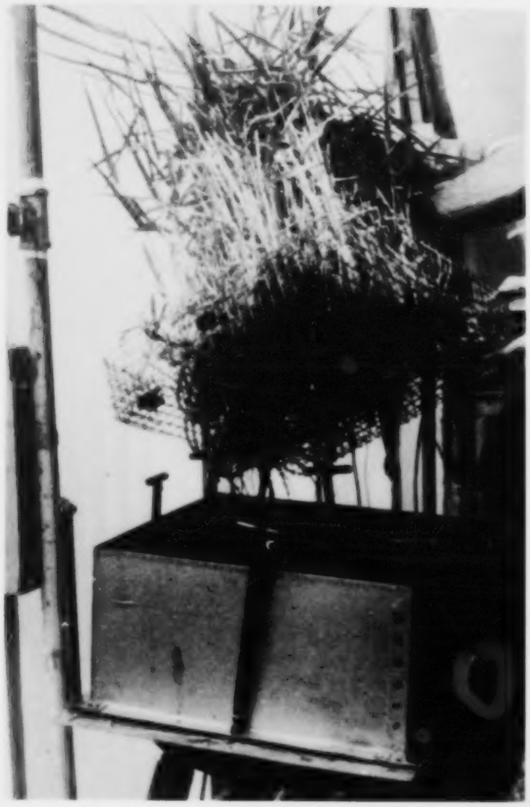
---Daily Loading---			Loading Schedule	Starting Date	Species
Cm/Day	m^3/m-d	Liters/Day			
6.9	2.49	1893	Continuous application	2-13-81	Phragmites, Cucumbers Canary grass
10.2	3.74	2839	Continuous application	4-16-81	Cattails/Bulrush, Phragmites, Canary Grass
20.3	7.47	5678	30 min. loading 30 min. pause Alternating cycle	5-11-81	Cattails/Bulrush, Phragmites, Canary Grass
40.6	14.94	11356	30 min. loading 30 min. pause Alternating cycle	6-11-81	Cattails/Bulrush, Phragmites, Canary Grass
6.9	2.49	1893	Continuous application	7- 2-81	Cattails/Bulrush Phragmites, Canary grass
10.2	3.74	2839	30 min loading 30 min. pause Alternating cycles		Cattails/Bulrush, Phragmites, Canary grass

The remaining 12.2 meter unit in the Brace house was used to monitor evapotranspiration water use and as a biomass control. Cumulative water use by this unit was measured twice a day by refilling the recirculating solution to a level controlled by a float valve. Both this unit and the third unit of the 36.6 meter system contained canary grass and underwent approximately the same temperature and nutrient conditions, and both units were harvested on the same days.

A.2.c. Root Analysis—

In an attempt to develop the relationship between the root surface area in contact with the wastewater, biomass accumulation and subsequent organic removal, root sampling devices were placed in the 36.6 meter (120 foot) pilot scale units at Cornell and Hanover.

For cattails, bulrush and phragmites, the root sampling device was a one-foot square basket made of 1.3 cm wire screen with 7.6 centimeter (3 inch) sides (see Figure 6.11). The basket was placed on a flat piece of sheet metal located in the bottom of the NFT unit. Plants were then placed



(a)

(b)

Figure 6.11. Root sampling devices: (a) cattail, bulrush and phragmites, (b) reed canary grass.

in the basket at the same density as the surrounding plants. The sheet metal plate had 8 screws mounted on it, so that a square sheet metal sleeve could be slipped around the basket and clamped down to the bottom plate. The entire sampling device was then extracted from the unit, including the plants, attached biomass, and solids entrapped by the root mass.

For reed canary grass, a similar device was developed, except that it incorporated a smaller surface area. A cylindrical 7.6 centimeter (3 inch) diameter basket was formed from 0.64 cm wire screen with 7.6 centimeter (3 inch) sides. The basket was placed on top of a 10.2 centimeter (4 inch) square piece of flat sheet metal, with a threaded center post extending from the sheet metal through the basket. This device was placed in the reed canary grass unit, and filled with the grass at a density similar to that of the surrounding grass. When sampled, a cylindrical sleeve was placed over the basket and tightened down with a flat bar and nut on the threaded rod so that the sample was extracted.

In the cattail/bulrush and phragmites units, three root sampling devices were placed in each unit, one at each position of 3.0, 7.6, and 10.7 meters (10, 20 and 35 feet) from the influent end. For each loading condition, the basket at the 7.6 meter position was sampled half-way through the condition; and the baskets at the 3.0 and 10.7 meter positions were sampled at the end of each condition. After sampling, the baskets were repositioned at their original locations with the vegetative contents intact.

In the reed canary grass, nine sampling baskets were placed, three at each location of 3.0, 7.6 and 10.7 meters (10, 25 and 35 feet) from the influent end. Basket sampling was similar to that for the cattail/bulrush and phragmites, except that in addition to sampling a previously unsampled basket, any baskets which had been previously sampled were extracted again. The purpose of this was to see if having previously extracted a basket would have any effect on the biomass accumulation.

After the baskets were removed from the units and the sleeve and bottom plate removed, the basket was suspended in a pan with a known volume of water and vigorously agitated to remove the attached biomass. This procedure was repeated with new water until the water stayed clean, and the roots appeared to be clean by visual inspection. Information collected from the sampled baskets included: volume of water entrapped; total and volatile solids contents of entrapped water and that collected from the root cleaning; weight of water and solids entrapped; estimated average root dimensions (length and diameter); root mat thickness; and a qualitative description of the roots (color, growth irregularities, etc.). Other data recorded were the wastewater depth in the unit during application and rest periods; a description of any algae or other growth in the wastewater; and a description of the top vegetative growth.

For reed canary grass, a volume displacement test was done to try to correlate root volume or surface area with biomass entrapment and organic removal. A similar approach was attempted for the cattail/bulrush and phragmites, but the volume of water displaced was too small to measure due to the large surface area of the one foot square sampling basket.

A.3. Bench Scale Units

A.3.a. Ken Post Greenhouse and Test Units--

The NFT project used glass-covered greenhouse space in the Kenneth Post greenhouse complex, which is under the direction of the Department of Floriculture and Ornamental Horticulture. The project had use of house 6-C, which is a glass-covered, corner greenhouse having a floor space of 7.6 x 7.6 meters (25 x 25 feet). The house was heated by steam radiators and ventilated by two automatic fans and a manual roof peak vent. This greenhouse maintained smaller temperature variations than the Brace house, which responded to ambient temperature and light conditions faster. Due to the nature of the Ken Post complex, this greenhouse was restricted to "clean solution" work (nutrient solutions devoid of carbon sources, which cause obnoxious odors).

Over the course of the project many different units were used in the Ken Post greenhouse. For plant adaptability and culturing work a series of 20 small units fed from a common reservoir were assembled. Figure 6.12 is a view of the system in operation. Each unit, measuring 22.8 cm wide by 3 m long with 7.6 cm sides (9 in. x 10 ft. x 3 in.), was lined with plastic. Five units together shared a common plywood base and were mounted on a large greenhouse bench (see Figure 6.13). The units were sloped approximately 1 percent. A centrifugal magnetic pump supplied a fertilizer-based nutrient solution to plastic pipe manifolds from which smaller tubes delivered solution to the individual units. Effluent from the units was collected in gutters and returned to the reservoir. Thirteen centimeter (5 inch) mesh wire screen was suspended 30 centimeters above the units to support plants as they grew. Various root shading materials (black plastic, white plastic, cheesecloth) were used to protect roots from clogging with algae.

A bench scale test system was built to test plant material production, nutrient uptake, evapotranspiration and contaminant removal. A schematic diagram of a single unit in this system is shown in Figure 6.14, and a picture of the system in operation is shown in Figure 6.15. The system consisted of six 10 cm (4 inch) by 1.5 m (5 foot) gutters with end pieces and tube connectors on both ends. The gutters were sloped at 1 percent. Each gutter section was connected to a solution reservoir by small tubes, and a master flex tubing pump (Cole Parmer 7545-00) circulated solution through each section. An additional water reservoir was suspended above the solution reservoir. This water maintained a constant volume in the solution reservoir by replacing water lost by evapotranspiration and thereby allowed measurement of this ET.

The remainder of the glasshouse space was filled with several other units over the course of the project. Large pilot scale units, smaller lengths of the same type unit, and high rate gross pollutant treatment systems were located in the glasshouse.

For growing and transporting plants to the Hanover greenhouse, 0.76 x 6.1 meter (2.5 x 20 foot) units were built. Crosspieces of 5 x 10 cm (2 x 4 inch) lumber connected 6.1 meter (20 foot) long, 5 x 15 cm (2 x 6 inch)

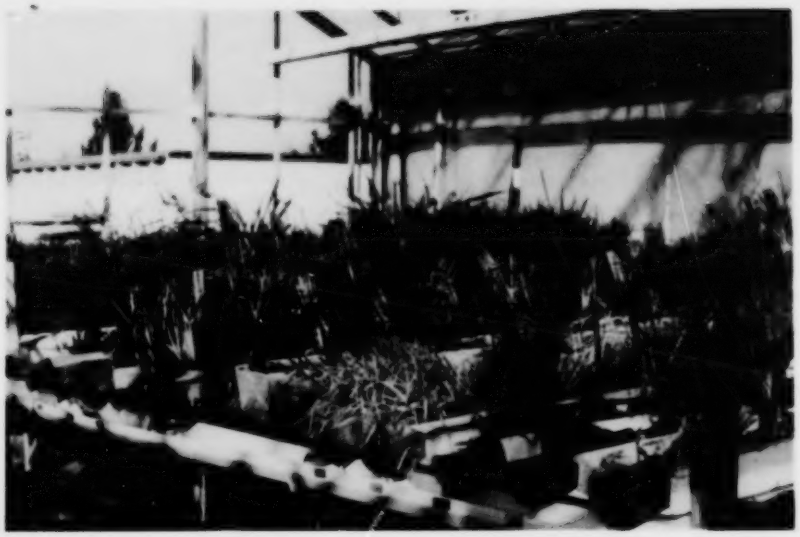


Figure 6.12. Post House 3 meter (10 ft) units in operation.

Figure 6.13. Construction of 3 meter (10 ft) units in Post House.

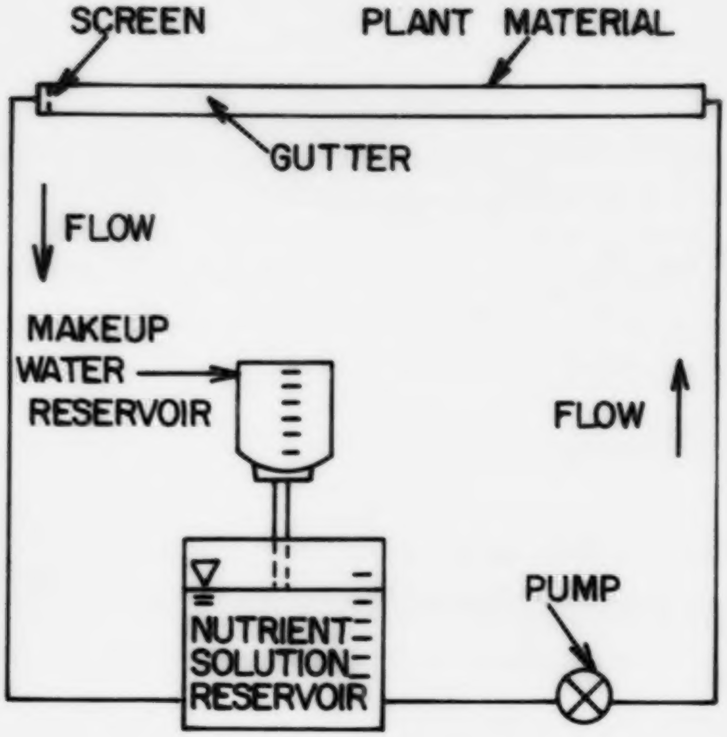


Figure 6.14. Schematic of Post House 1.5 meter (5 ft) unit.

Figure 6.15. Post House 1.5 meter (5 ft) unit in operation.

stringers, as shown in Figure 6.16. A 1.3 cm (half inch) plywood floor was placed on the crosspiece and stringers, and plywood sides were attached to the stringers. Legs of pressure-treated 10 x 10 cm (4 x 4 inch) lumber cut at various lengths were bolted into the corners of the units. As in the reconstructed unit in the Brace house, these units contained no cascades for reaeration. The floor was made of three abutting sheets of plywood.

A.3.b. Loading Rates Schedule and Plant Species Tested--

Nine experimental runs were completed in the bench scale units at Ken Post laboratory. These experiments ran from November 1980 through July 1981 and are described below and summarized in Table 6.5. Some of the experiments were performed in parallel with the bench scale unit in Hanover, New Hampshire.

Experiments 1 through 4 were performed to determine the rates at which plants took up nitrogen, phosphorus and cadmium from solution. Various plants were tested on synthetic wastewater without the carbon source to define the nutrient uptake rates and evapotranspiration water use. These recirculating units were sampled intensively (four times) the first day, once each of the following days for a week, and every other day thereafter. These experiments ran approximately two weeks. In these and subsequent experiments, a gutter receiving flow but containing no plant materials was used as a control. This control allowed comparisons of evaporation and transpiration by different plants.

Experiment 5 was similar to earlier experiments except that the carbon source was introduced and analyses included chemical oxygen demand and solids. All species in this experiment except cucumbers were grown on wastewater in the Hanover greenhouse before being placed in the units.

Experiments 6 and 8 tested the effects of salt concentration on evapotranspiration and nutrient uptake. In experiment 6 the salt used was an equimolar mixture of NaCl and $CaCl_2$, and included concentrations of 0, 15, 30, 60 and 120 milliequivalents per liter. The largest of these is greater than that of any irrigation water used in the arid west. All units except the control contained reed canary grass, which, being a grass, is tolerant to salts relative to other test species. In this experiment the calcium (Ca) tended to precipitate with the ammonia and phosphate, making them unavailable to the plant and lowering the salt content. To remedy this, experiment 8 used NaCl only, with other conditions remaining the same. The sampling schedule and duration of these experiments were the same as earlier experiments.

Experiments 7 and 9 were simulations of various loading rates. This allowed for testing of high loading rates not tested in the pilot scale units and simultaneous testing of loading rates under identical light and temperature conditions. Canary grass filled five units, and the sixth was an empty control. Flow rates included 200, 160, 75, 42 and 21 mℓ per minute, which corresponded to area loading rates of 182.9, 147.3, 68.6, 38.1 and 20.3 centimeters (72, 58, 27, 15 and 8 inches) per day, respectively. In these

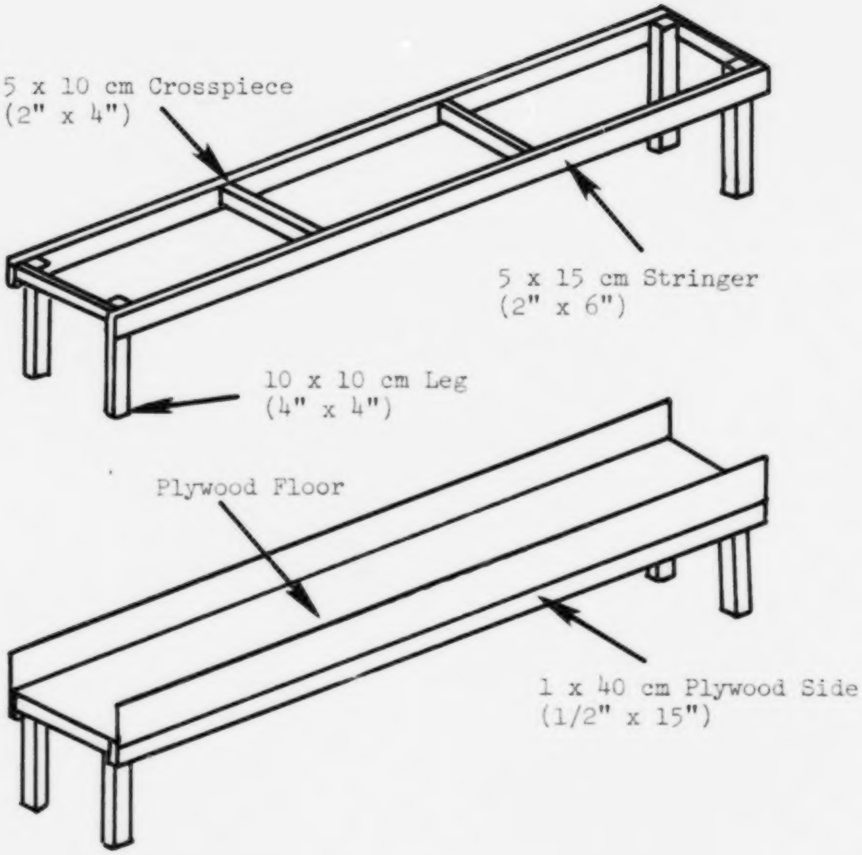


Figure 6.16. Superstructure (above) and plywood covered floor (below) schematics of 5.1 m (20 foot) portable units.

experiments, the apparatus was operated as a once-through system, with the effluent being wasted and the synthetic wastewater being made fresh every 12 hours. These units were allowed to come to equilibrium over a period of a week, which included two complete analyses of the effluent. Then the units were tested for 3 or 4 consecutive days to define their steady state characteristics. Analyses included nutrients plus COD, BOD and solids.

TABLE 6.5. CORNELL BENCH SCALE EXPERIMENTS CONDUCTED IN THE GLASS COVERED GREENHOUSE (KEN POST LABORATORY)

Experiment No.	Starting Date	Additional Amendments to Nutrient Solution	Test Species	Recycle or 1 Pass
1	11- 9-80	None	Soft rush, phragmites cattail, canary grass	Recycle
2	1-19-81	None	Phragmites, canary grass, woolgrass, soft rush, bristly sedge, control	Recycle
3	2-27-81	None	Millet, bristly sedge, canary grass, soft rush, napier grass, control	Recycle
4	3-18-81	None	Cucumber, phragmites, canary grass, bulrush cattail, control	Recycle
5	4-28-81	Carbon source	Cucumber, Canary grass, Bulrush, Cattail, Phragmites, control	Recycle
6	5-13-81	Salts	Canary grass, control	Recycle
7	6-11-81	Carbon source	Canary grass, control	One pass
8	7- 2-81	Salt	Canary grass, control	Recycle
9	7-17-81	Carbon source	Canary grass, control	One pass

A.4. Analytical Methods

In the analysis of 12.2 meter canary grass units, one liter of sample was collected at the distribution box, Point A, Point B, and above the effluent barrel (for locations see Figure 6.2). At high flow rates, much settled matter was flushed into the sampling ports immediately after their opening, and this necessitated waiting for the establishment of a uniform flow before taking the sample. At each point, samples from each port were shaken and composited to obtain a representative sample. For the analysis of the pilot 36.6 meter (120 foot) units, one liter samples were collected at the end of each 12.2 meter (40 foot) unit. Again, samples were mixed and composited. During intermittent operation, samples were taken during times of uniform high flow. From the bench scale unit 75 or 200 mℓ samples were taken, depending on whether the analyses included COD and solids, or nutrients and Cd only.

All gravimetric and chemical analyses were carried out in accordance with Standard Methods for the Examination of Water and Wastewater (APHA, et al., 1976), with the exception of the Chemical Oxygen Demand and Total Nitrogen analyses, which will be described later.

Filterable residue was determined by passing 500 mℓ of sample through glass fiber filters in Gooch crucibles. The filtrate, along with unfiltered samples, was used in subsequent analyses. Total residue was determined by adding 100 mℓ of samples to crucibles. All crucibles were dried overnight at 103°C. Following weighing, crucibles were ashed at 550°C for one hour to determine fixed and volatile fractions of the residue.

Nitrogen species were determined by distillation and titration, using 50 or 100 mℓ sample volumes. Ammonia was determined by the preliminary distillation method using phosphate buffer. Nitrate was determined on the same sample after the addition of Devarda's alloy for nitrate reduction. Organic nitrogen was determined by the Kjeldahl method. Values for urea were obtained by incubating samples and blanks with urease enzyme (AOAC, 1960) and then distilling urea plus ammonia.

To determine total N on a wastewater sample (other than totaling N species) the procedure of Raveh and Avnimelech (1979) was used. The procedure uses a potassium persulfate oxidation in an autoclave, followed by reduction of nitrates and nitrites to ammonium with Devarda's alloy. Ammonia nitrogen was then determined by distillation.

Orthophosphate was determined on appropriately diluted samples by the stannous chloride method, using a Bausch & Lomb Spectronic 70 spectrometer.

The azide modification of the iodometric method was used to determine dissolved oxygen content.

The pH was measured on a Beckman Zeromatic SS-3 pH meter.

For cadmium, samples were preserved in 1% nitric acid and analyzed on a Perkin Elmer Model 305 atomic absorption spectrophotometer.

To determine the chemical oxygen demand, the colorimetric method described by Knechtel (1978) was used. Sample and reagent volumes proportional to, but smaller than, those used in Standard Methods were added to Kimax 25 x 150 mm culture tubes with teflon-lined caps. Tubes were then inverted several times for mixing, placed in a 150°C oven for two hours and cooled in a water bath. The appearance of Cr III in standards, blanks, and samples was determined by absorbance readings at 600 nm on the Spectronic 70 spectrometer. Culture tubes were placed directly in the Spectronic 70 after cooling to room temperature.

For plant tissue cadmium content, foliar or root samples of 0.50 or 0.75 g were mixed with 5 mℓ concentrated HNO_3 and stored overnight. They were then placed on a microKjeldahl apparatus and heated until the fuming subsided and solution cleared. Samples were then filtered, brought to a known volume, and analyzed for cadmium in the same manner as water samples.

Hydraulic retention time (HRT) of the test unit was compared to control units which received no wastewater flow. A chloride spike was used to determine the hydraulic retention time of the test and control units under various operating conditions. Ten grams of NaCl, dissolved in one liter of water, were added where the water entered the grass, and periodic samples were taken at the sampling ports and effluent stream. Chloride (Cl^-) analysis was conducted using an Orion specific Cl^- electrode and model 407A Ionalizer meter. In intermittently operated systems, hydrograph data were used to correct for the effluent flow irregularity. Hydraulic retention time was calculated using the formula:

$$HRT = \frac{\sum t_i \, C_i \, \Delta t_i}{\sum \Delta t_i \, C_i} \qquad (6.1)$$

where

t_i = time of sample

C_i = Cl^- concentration, and

Δt_i = sampling interval

B. PROCESS DEFINITION WITH SEWAGE - STUDIES AT HANOVER, NEW HAMPSHIRE AND CAYUGA HEIGHTS, NEW YORK

B.1. Pilot Scale Units

B.1.a. CRREL Greenhouse and Test Units--

The NFT model used in the CRREL study was a plywood tray 0.61 m (2 ft.) wide and 12.2 m (40 ft.) long lined with plastic and installed at a 5 percent slope. Due to space restrictions in the greenhouse, two troughs 6.1 m (20 ft.) long were installed beside each other. The effluent from the first trough flowed by gravity to the high end of the second trough which sloped in the opposite direction. Figures 6.17 and 6.18 show the system as installed in the greenhouse, and Figure 6.19 is a schematic of the system showing its major components. As shown in Figure 6.19, the rate of flow onto the system was controlled by adjusting the flow control valve. The length of the wastewater applications and resting periods was adjusted using

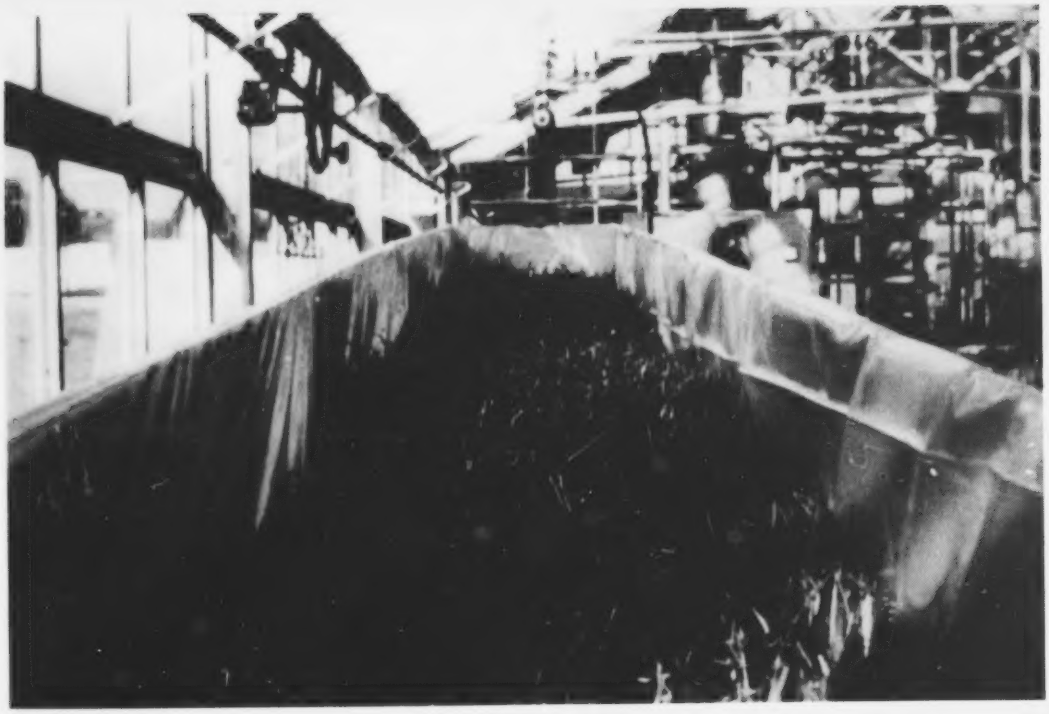


Figure 6.17. Experimental NFT unit for primary settled domestic sewage studies at Cornell.

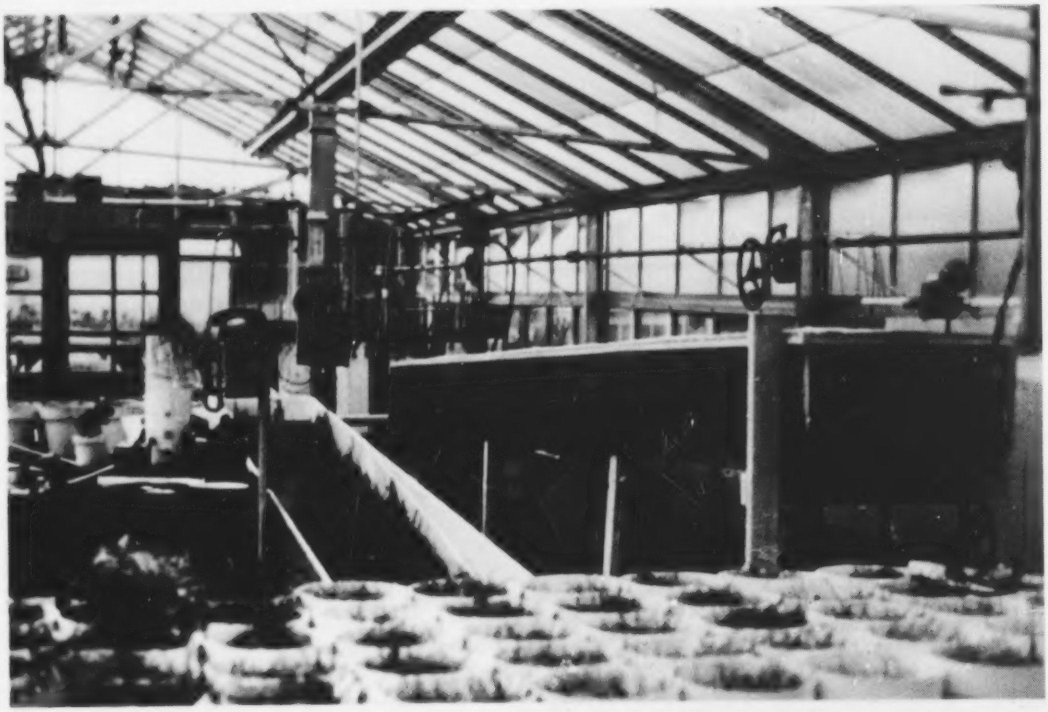


Figure 6.18. View of initial placement of reed canary grass washed sod just after the first harvest at CRREL.

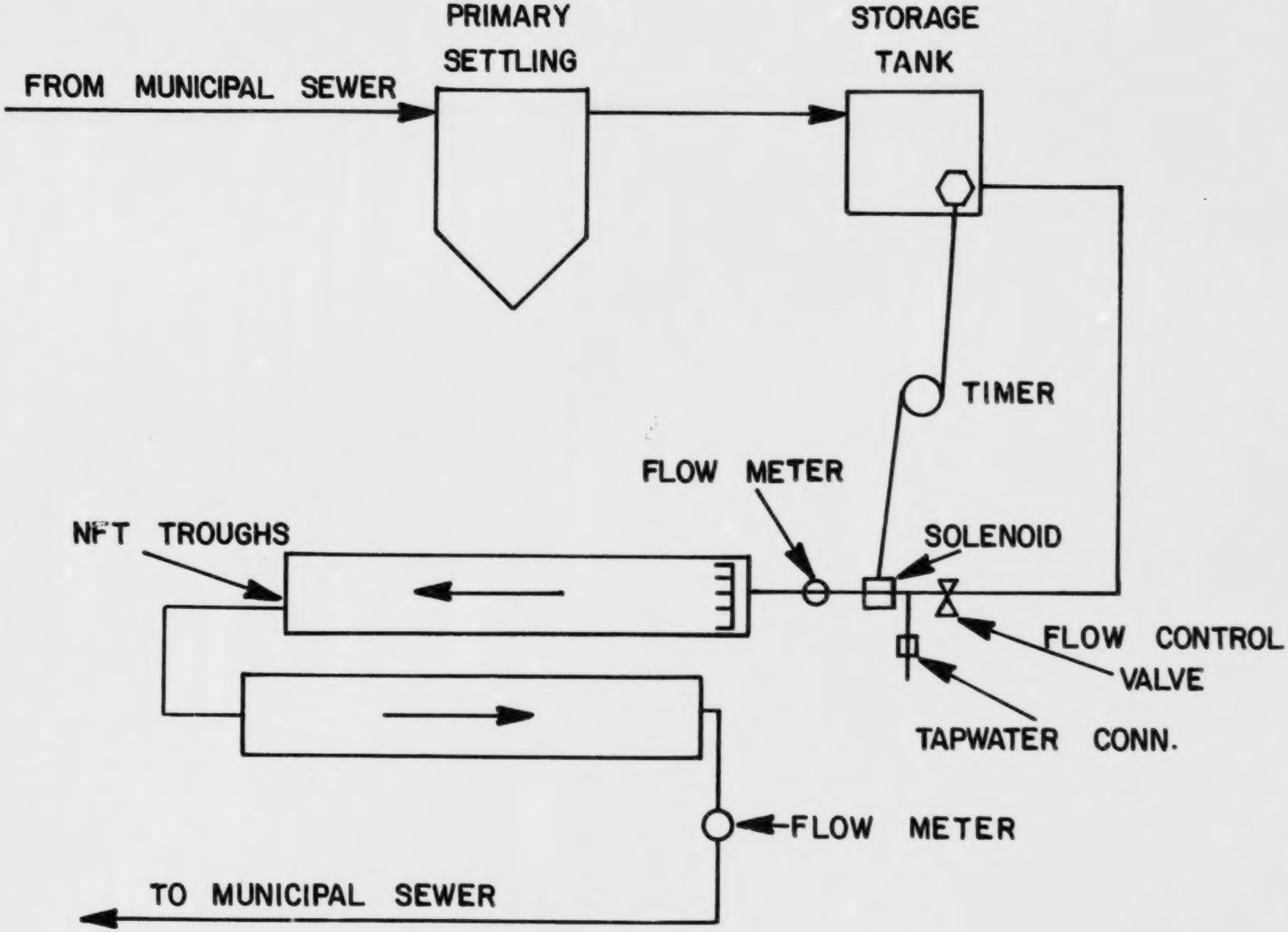


Figure 6.19. Schematic diagram of the CRREL NFT system.

a timer capable of allowing an application period of zero to 30 minutes and a rest period of up to 60 minutes. The two meters in Figure 6.19 were used to measure total flows in and out of the system. The meter in the influent line was also used to measure the instantaneous flow rate onto the system during any particular application cycle. This capability was used in conjunction with the flow control valve to adjust the amount of wastewater applied per cycle and therefore the amount of wastewater applied each day. The system also included the capability of applying tap water in the event of mechanical failure of the wastewater delivery and application system. The crop used in this study was reed canary grass sod that had the soil washed from the roots prior to being placed in the model.

B.1.b. CRREL Loading Rates Schedule--

Table 6.6 summarizes the testing program for the sewage treatment study in Phase 0. Due to the lack of information on the use of the NFT to treat wastewater, the investigators relied upon their knowledge of the overland flow method of wastewater treatment, thereby deciding initially to use application rates of 10.2, 20.3, and 40.6 centimeters (4, 8, and 16 inches) per day of wastewater. These rates gave volumes of 757, 1514, and 3028 liters (200, 400, and 800 gallons) per day, respectively.

In an effort to maintain aerobic conditions in the root zone, an intermittent application schedule was used. The investigators initially decided to use a 24 hr/day schedule consisting of 3.14 liters (0.83 gallons) per minute for 10 minutes followed by a 50-minute rest period. This was followed by a schedule consisting of 1.59 liters (0.42 gallons) per minute continuously for 8 hours followed by a 16-hour rest period. The next schedule consisted of 3.14 liters (0.83 gallons) per minute for 20 minutes followed by a 40-minute rest period, for 12 consecutive hours. The system then rested for 12 hours. The above schedules were all intended to apply 10.2 centimeters (4 inches) per day. Subsequently, an application rate of 3.14 liters (0.83 gallons) per minute for 10 minutes followed by a 50-minute rest period for 12 consecutive hours followed by a 12-hour rest period was implemented. This was intended to apply 5.1 centimeters (2 inches) per day. Finally, in order to apply 20.3 centimeters (8 inches) per day, an appliication schedule of 4.16 liters (1.1 gallons) per minute for 20 minutes followed by a 40-minute rest period for 18 consecutive hours was used.

At the beginning of Phase 1, CRREL continued testing reed canary grass in the 12.2 meter (40 foot) unit. Table 6.7 shows the specific conditions tested during this period. The conditions were similar to those tested in Phase 0, but allowed the grass and root system to become acclimated to the wastewater flow over a longer period of time than in Phase 0. The instantaneous flow rate onto the grass was identical in each case, and loading rates were controlled by manipulating the length of the application period. This unit was killed early in Phase 1, so the duration of experiments with this setup is limited. The cause of death of the plants was traced to a combination of operating conditions and a large spill of ammonia at CRREL.

TABLE 6.6. SUMMARY OF CRREL STUDY ACTIVITIES IN THE 12.2 m PILOT SCALE SYSTEM DURING PHASE 0

Dates	Activity
13 Nov 79 - 31 Dec 79	Troughs constructed and installed; plumbing installed, tested, and modified as required.
15 Nov 79	Reed canary grass placed in troughs.
16 Nov 79 - 2 Dec 79	Approximately 380 ℓ/d of sewage or tap water applied intermittently (0.62 m^3/m-d).
3 Dec 79 - 10 Dec 79	Hydraulic retention time studies conducted.
3 Dec 79 - 18 Dec 79	190 - 1890 ℓ/d of wastewater or tap water applied intermittently.
19 Dec 79 - 27 Dec 79	An average of 295 ℓ/d of tap water applied, 10 min. on - 50 min. off, 24 hours per day (0.48 m^3/m-d).
28 Dec 79 - 30 Dec 79	An average of 990 ℓ/d of wastewater applied intermittently.
31 Dec 79 - 11 Jan 80	Automated application of sewage, 10 min. on - 50 min. off, 24 hours per day, to give 1.25 m^3/m-d (760 ℓ/d).
12 Jan 80 - 13 Jan 80	System rested.
14 Jan 80 - 18 Jan 80	Continuous application of sewage for 8 hours followed by 16 hour rest period to give 1.25 m^3/m-d (760 ℓ/d).
19 Jan 80 - 30 Jan 80	Automated application of sewage, 20 min. on - 40 min. off for 12 hours per day, rest 12 hours per day, to give 1.25 m^3/m-d (760 ℓ).
31 Jan 80 - 8 Feb 80	Automated application of sewage, 10 min. on - 50 min. off for 12 hours per day to give 0.62 m^3/m-d (380 ℓ).
9 Feb 80 - 13 Feb 80	Automated application of sewage, 20 min. on - 40 min. off for 18 hours per day, rest for 6 hours per day, to give 2.48 m^3/m-d (1510 ℓ).

TABLE 6.7. LOADING CONDITIONS TESTED IN THE 12.2 m PILOT SCALE SYSTEM IN THE CRREL GREENHOUSE DURING PHASE 1

Dates	Loading Rate (cm/day)	(liters/day)	(m^3/m-d)	Application Period (minutes per hour)
15 Feb 80 - 11 Apr 80	5.1	379	0.62	5
12 Apr 80 - 13 June 80	10.2	757	1.24	10
14 June 80 - 30 June 80*	20.3	1514	2.48	20

*Unit terminated due to death of plants shortly after this date.

B.1.c. Hanover Greenhouse and Test Units—

In the summer of 1980 larger systems were constructed to expand the scope of the study. It appeared that the desired treatment from the hypothesized three-part system (rough filtering, nutrient removal and polishing) was not realized from the 12.2 or 24.4 meter (40 or 80 foot) units. In the Cornell Brace house, 12.2 meter (40 foot) units would be connected to provide a sufficiently long system for synthetic sewage testing, and a new temporary greenhouse structure would be erected at a sewage treatment plant.

The Town of Hanover, New Hampshire, sewage treatment plant was selected because it offered the following advantages:

1. a medium to low strength domestic sewage with few industrial sources;

2. a site conducive to greenhouse location;

3. city officials and operators interested and willing to cooperate;

4. close proximity to CRREL, which could perform analyses.

In mid-November 1980 a subcontract was executed between Cornell and the Town of Hanover; and a Cornell crew, aided by local contractors and the sewage plant personnel, began construction. The greenhouse was sited on the south-facing side of the treatment plant building and attached digester. The site sloped downward to the west, necessitating a retaining wall and backfill to level the site. The location of the greenhouse in relation to the plant is shown in Figure 6.20.

The greenhouse choice was based on minimum cost and ease of construction. The design chosen was the "Twenty-One" style wooden gusset greenhouse invented and described by Sheldrake and Sayles (1977). This house is constructed from simple trusses strenthened with external plywood gussets and covered with two layers of plastic attached from the outside. Gusset houses are fairly simple to erect and can be constructed by relatively

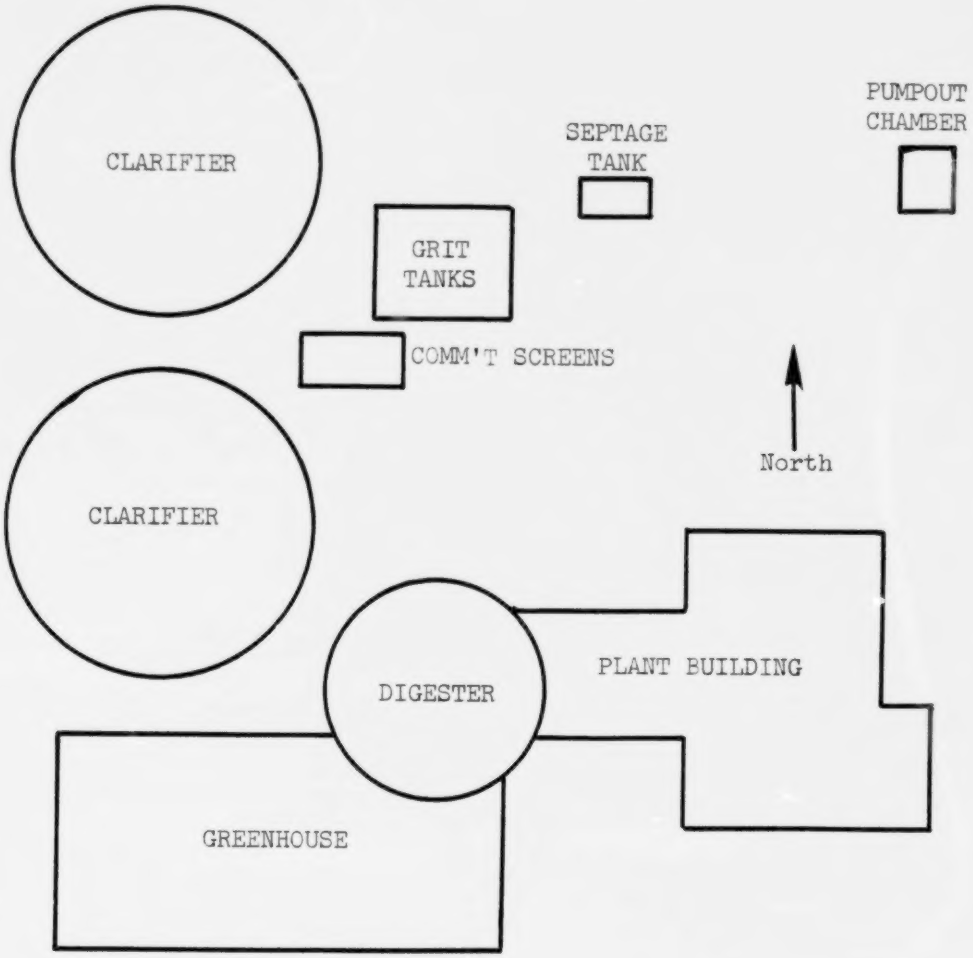


Figure 6.20. Site plan of greenhouse and Hanover, New Hampshire, sewage treatment plant.

unskilled laborers using standard stock lumber. One complicating feature of the Hanover site was the necessity of building the greenhouse around the curved surface of the digester wall. The trusses, which were attached to posts on 1.2 meter (4 foot) centers, were made of unequal length around the digester, and the small area of roof above this curved section was covered with a solid rather than plastic outer covering. Figure 6.21 shows the construction of unequal trusses around the digester. The completed greenhouse is shown in Figure 6.22.

The greenhouse was 18.3 meters (60 feet) long and 9.1 meters (30 feet) wide overall. However, the digester took up almost one-fourth of this space, which resulted in a usable floor area of approximately 130 square meters (1400 square feet). This was adequate space to construct two 36.6 meter (120 foot) systems. The first unit was built to parallel the 36.6 meter (120 foot) system constructed in the Cornell Brace house, and was constructed from portable 6.1 meter (20 foot) sections described earlier and illustrated in Figure 6.16. Six of these sections were joined to make up three 12.2 meter (40 foot) lengths and connected similarly to the Brace house system. A second set of six 6.1 meter (20 foot) sections was joined by gutters to form a single gravity fed unit. The arrangement of trays, direction of flow of wastewater, and associated equipment are shown schematically in Figure 6.23. The interior of the greenhouse and trays under construction are shown in Figure 6.24.

Due to problems experienced with the chlorination practice of the treatment facility (chlorine was added upstream from the primary clarifier), a small primary sedimentation tank was constructed. It consisted of modifying a little used pump out chamber located at the head works of the plant. A small portion of the raw sewage entering the treatment plant was diverted to a 2.1 m x 2.1 m (7 x 7 foot) pumpout chamber, which acted as a primary clarifier. This sewage, which resembled primary settled sewage, was then used in the greenhouse. The tank had an upper overflow pipe to allow a continuous supply of fresh sewage to be pumped into the greenhouse and a lower waste line to remove solids settling in the tank. A 0.19 kilowatt (1/4 horsepower) pump agitated the tank contents and was capable of delivering any desired flow. In the main testing system (shown as unit A in Figure 6.23), primary settled wastewater was pumped to the supply tank and then pumped onto the first 12.2 meter (40 foot) unit as needed. At the end of the first level 12.2 meter (40 foot) unit, the sewage was pumped up to the second unit from a catch barrel. At the end of the first testing condition, the first unit was raised so that wastewater flowed by gravity to the next unit. This unit was sloped at 2% and wasted directly into the third, which was also sloped. (See Figure 6.10 for a description of the identical Brace house system.)

In the second 36.6 meter (120 foot) system, sewage flowed from the supply tank to a reservoir below the first unit. It was then pumped up to the first tray from which it flowed by gravity through each subsequent tray.

A desk and laboratory work space were installed in the southwest corner of the greenhouse. This space was used for BOD analysis, microscopic work,

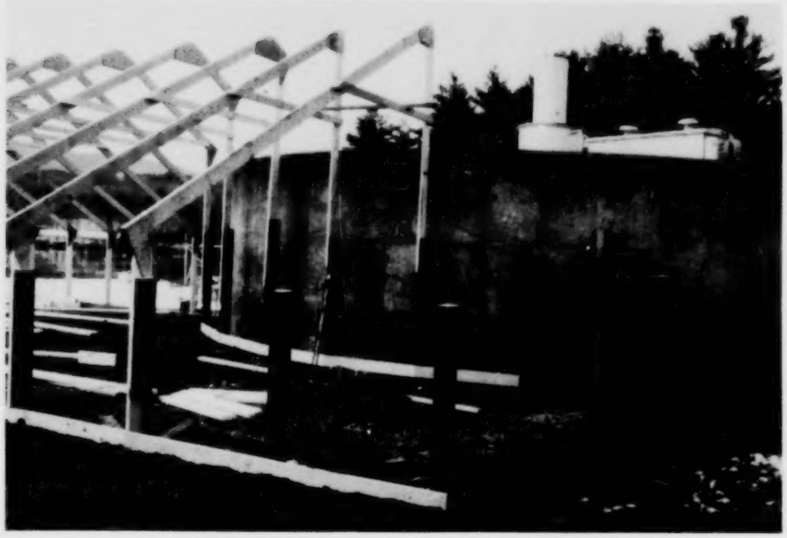


Figure 6.21. Attachment of trusses to posts during construction of the Hanover greenhouse. Trusses were built of unequal lengths to fit around the digester wall.

Figure 6.22. View of the plastic covered Hanover greenhouse, treatment plant building, and surrounding grounds.

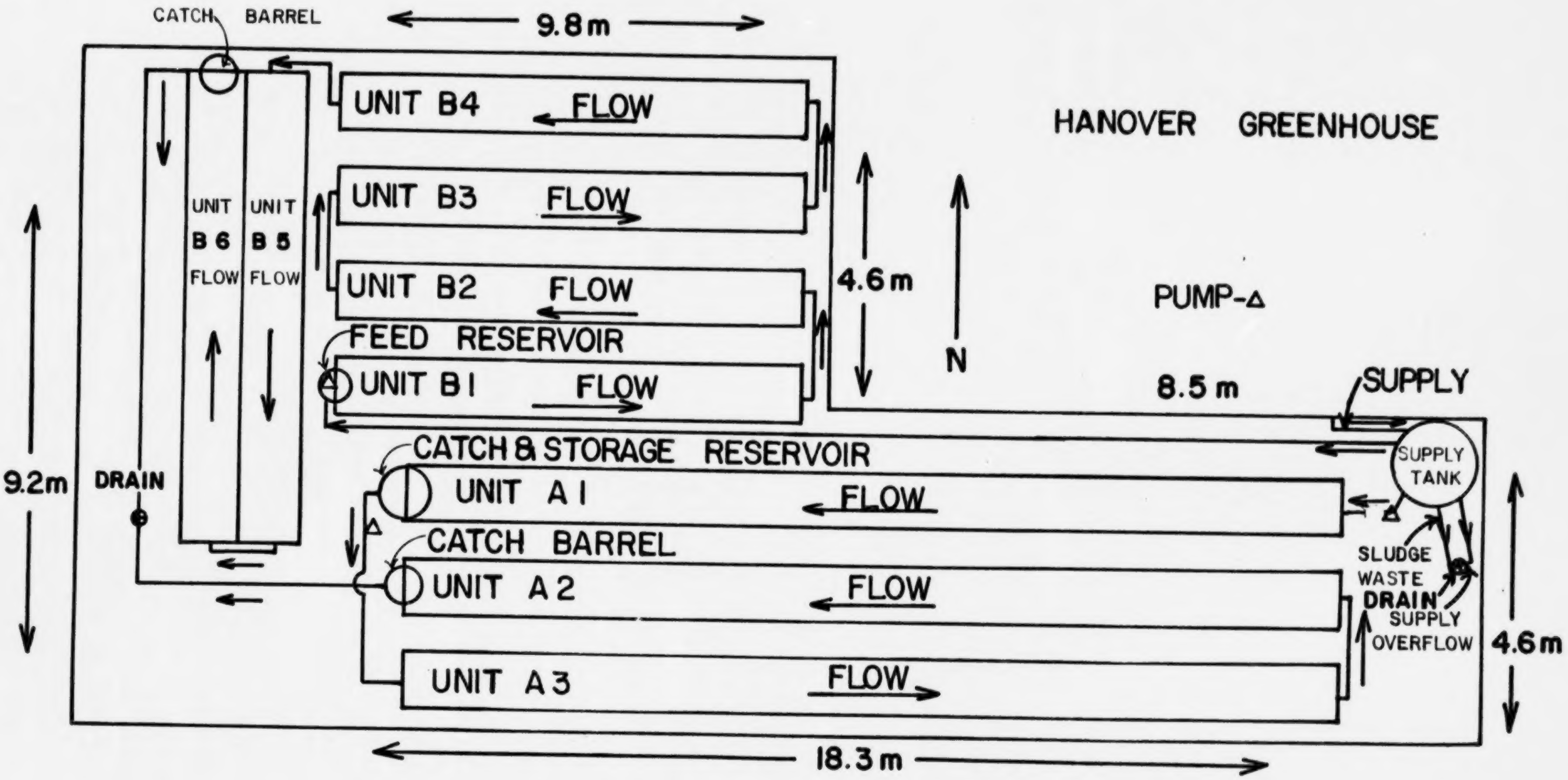


Figure 6.23. Schematic diagram of units in the Hanover greenhouse.

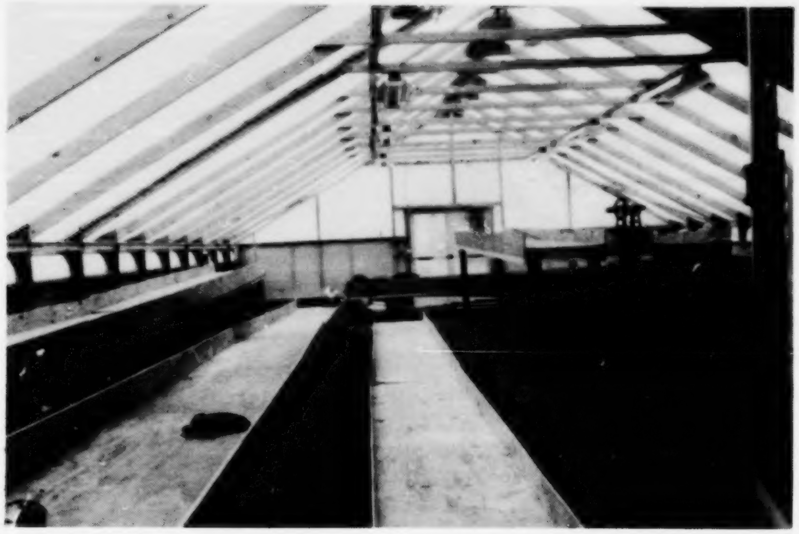


Figure 6.24. The interior of the Hanover greenhouse, treatment plant building, and surrounding grounds.

plant preparation and manipulation, and equipment storage. The bench scale unit was placed in a small area near the digester wall.

B.1.d. Hanover Loading Rates Schedule and Plant Species Tested--

Over the course of spring of 1981 several loading conditions were tested in the Hanover greenhouse pilot unit. These conditions are summarized in Table 6.8. Several changes made over the course of this testing period should be noted. As in the Cornell Brace house system, the cucumbers did not perform well in the initial loading condition, and plant species were rearranged following this first testing period. The first 12.2 meter unit had a small slope, and this was not removed until the third condition. Toward the end of the second condition and throughout the third condition, the reed canary grass did not perform well and began to die. This was in contrast to the Cornell Brace house canary grass which appeared healthy. In an attempt to rejuvenate the grass, the system was not pushed to the 40.6 centimeter (16 inch) per day loading as was the Cornell unit, but rather the system was dropped back to a 5.1 centimeter (2 inch) per day loading. The reed canary grass eventually recovered under this low loading. Experiments in the Hanover facility were terminated in August, 1981. The facility was converted to a storage area for the treatment plant in October, 1981.

TABLE 6.8 LOADING CONDITIONS TESTED IN THE PILOT SCALE UNIT AT THE HANOVER TREATMENT PLANT

Dates	Loading Rate (cm/day)	(liters/day)	(m^3/m-d)	Plant Species	Application Mode
2/13/81- 3/20/81	6.9	1893	2.49	Phragmites Cucumbers Reed canary grass	Continuous
4/13/81- 5/ 8/81	10.2	2839	3.74	Cattail/bulrush Phragmites Reed canary grass	Intermittent 15 minutes application 15 min. rest
5/9/81- 6/3/81	20.3	5678	7.47	Cattail/bulrush Phragmites Reed canary grass	Intermittent 30 minutes application 30 min. rest
6/13/81- 8/21/81	5.1	1420	1.87	Cattail/bulrush Phragmites Reed canary grass	Intermittent 30 minutes application 30 min. rest Rest overnight

B.1.e. Root Analysis

Root sampling devices similar to those used at Cornell were installed in Unit 1 at the Hanover greenhouse. The sampling procedure and frequency was identical to that performed at Cornell, described in a previous section. Root sampling baskets were extracted both at the midpoint and at the end of each loading condition.

Periodically, a qualitative description of the plants and root systems in Unit 2 was recorded. Unit 2 contained a variety of species, constantly receiving sewage at a rate of 6.9 cm/day throughout the study. Information collected on Unit 2 included: plant height, coloring and condition; estimated leaf surface area (when applicable); appearance of accumulated algae and other growth in the water and under the plants; and description of material entrapped by the root mass. The measurements and descriptions of the root mass included: approximate average root length and diameter; the approximate density and arrangement of the roots; apparent new growth; root mat thickness; and any irregularities in color, texture and uniformity. Observations were documented by photographs whenever possible.

B.1.f. CRREL Analytical Procedures--

Grab samples of the applied wastewater and of the runoff were delivered to the water chemistry and environmental engineering laboratories at CRREL where they were analyzed for nitrogen species, orthophosphate, total organic carbon, solids, turbidity, pH, biochemical oxygen demand, and fecal coliform bacteria, in accordance with Standard Methods (APHA et al., 1976). Total nitrogen analyses were performed by the same persulfate digestion procedure used at Cornell, which was described earlier. In addition, CRREL performed total phosphorus analyses on an aliquot of sample removed from the total nitrogen digest before Devarda's metal addition. Both volatile and nonvolatile trace organic determinations were conducted by CRREL personnel using a gas chromatograph - mass spectrometer combination. Not all samples were analyzed for all these parameters. Hydraulic retention time determinations were identical to the procedures used at Cornell. Samples for Cd analysis were shipped to Cornell. Grass was harvested periodically, and fresh and dry weights were obtained. A subsample of grass from the last harvest was sent to Cornell or another laboratory for tissue analysis. Daily, maximum, and minimum temperatures in the greenhouse were recorded, as were incoming solar radiation measurements.

B.2. Bench Scale Units

B.2.a. Hanover Bench Scale Units and Experiment Schedule--

A 1.5 meter (5 foot) bench scale system identical to the one in the Ken Post greenhouse was set up to test plant material production, nutrient uptake, carbon and cadmium removal, and evapotranspiration. Four of the plant species tested came from the main unit. An additional species was taken from the culturing unit to make a total of five species and a control in each run. All bench scale systems were fed sewage. Sewage was obtained by dipping a small bucket below the surface of the 1893 liter (500 gallon) reservoir and allowing it to fill. Seven and one-half liters were measured into each of the six reservoirs and circulated through the trays at a rate of 200 mℓ/min. Stirrers were used to completely mix reservoirs during the first run only.

Four experimental runs, each lasting for a two-week period, were completed. These experiments ran from March 1981 to July 1981 and are described below and summarized in Table 6.9. The objective of the bench scale experiments was to determine the correlation between removal efficiency and loading rate by using plants acclimated to the various loading rates tested in Unit 1.

TABLE 6.9. HANOVER GREENHOUSE BENCH SCALE EXPERIMENTS

Experiment No.	Starting Date, 1981	Analysis Run	Test Species	Acclimated Loading Rate	Source of Plant Material
1	3/23	N, P	Cucumbers		Unit 1
		COD Solids	Reed Canary Grass (RCG)		Unit 1
		ET	Phragmites	6.9 cm/day	Unit 1
			Bulrush		Unit 2
			Cattails		Unit 2
			Control		
2	4/17	N, P	Roses	6.9 cm/day	Unit 2
		COD	RCG	6.9 cm/day	Unit 1
		BOD	Phragmites	6.9 cm/day	Unit 1
		Solids	Bulrush	6.9 cm/day	Unit 1
		ET	Cattails	6.9 cm/day	Unit 1
			Control	6.9 cm/day	
3	5/ 7	N, P	Bulrush	10.2 cm/day	Unit 1
		COD	RCG	10.2 cm/day	Unit 1
		BOD	Phragmites	10.2 cm/day	Unit 1
		Solids	Cattails	10.2 cm/day	Unit 1
		ET	Napier grass	6.9 cm/day	Unit 2
			Control		
4	5/21	N, P	Tomatoes	6.9 cm/day	Unit 2
		COD	RCG	20.3 cm/day	Unit 1
		BOD	Bulrush	20.3 cm/day	Unit 1
		Solids	Phragmites	20.3 cm/day	Unit 1
		ET	Cattail	20.3 cm/day	Unit 1
			Control		
5	7/ 1	N, COD	RCG	20.3 cm/day	Unit 1
		BOD			
		Solids			

The units were sampled every four hours for the first day, twice the second day (12-hour intervals), once each of the next 5 days, and every other day for the remaining 7 days. BOD's were run on site. Solids samples were cooled, and COD and N samples were acidified to pH<2 using conc. H_2SO_4 (36N) and shipped to Cornell for analysis. Evapotranspiration readings were taken twice daily. In addition to the daily sampling, all species and the control were drained and weighed before and after each experimental run to determine the increase in biomass during the experimental period.

Experiment 5 evaluated BOD removal efficiency using reed canary grass at various loading rates. The apparatus and operating procedure were identical to that of experiments 7 and 9 performed in the Ken Post greenhouse at Cornell. Masterflex positive displacement pumps fed sewage to the unit in a one-pass flow scheme from an 1893 liter (500 gallon) reservoir. The experiment ran for 13 days. Samples were taken on days 1, 3, 7, 11, 12 and 13 and were handled in the same manner as they were for the previous four experimental runs. On the day of sampling, volumes retained in each tray were measured after sampling. Pumps were shut down and trays were allowed to drain for two hours. The volume of sewage collected was measured as an indicator of the HRT of each tray.

B.2.b. Cayuga Heights Greenhouse, Bench Scale Units and Experiment Schedule--

From clarifier design parameters, it was evident that the NFT systems designed and used in early experiments were not optimal for removing suspended solids. This had two detrimental effects on the system--first, a long length of unit was necessary to perform the required treatment, and second, the solids which passed through the first part of the system could inhibit the more valuable but delicate plants in downstream portions. The typical tray design did not handle solids well because at higher loading rates the velocity in the thin films was too great to allow for sedimentation. An earlier attempt to improve solids handling was to remove the slope from the first unit in three-unit systems. While leveling the unit, in combination with using plants with large roots, did improve solids removal, its performance was still below expectations. For these reasons a new system was designed consisting of sequentially filled chambers where root zones could be alternately flooded with wastewater and drawn down for aeration and drying. In this way the sedimentation process could be optimized and the root zone could provide a filter for entrappment of solids and a foundation for microbial attack. By raising and lowering the wastewater level slowly, flushing of the root zone and trapped material would be minimized until such time as solids removal from the unit was desired.

The purpose of these experiments was threefold. The first purpose was to find out whether a system with a high flow capacity would be capable of performing a large portion of the solids removal (settling and/or metabolism). Could a system be designed which would contain the sewage long enough for significant treatment and minimize solids flushing when the batch of wastewater was changed? The second purpose was to see which plants could tolerate submersion in a fairly deep (30 cm) pool of standing wastewater with periodic drying. The third purpose was to investigate the role of this type of unit in an overall treatment scheme. Significant improvement over earlier NFT designs in solids handling capability and organic removal rate could lead to its use as a pretreatment step or as a possible replacement for conventional primary and secondary treatment units.

Since the Cayuga Heights system was intended for summer operation only, a minimal greenhouse cover was built. A single sheet of polyethylene was used to cover a wooden frame of lean-to design enclosing an area of approximately 3 x 6 m. The enclosure had a southern exposure, and abutted an anaerobic digester and associated building, which provided protection from north and northwest winds. The enclosure provided protection from early frosts and rain. Openings were provided at both ends so air could move freely through the greenhouse. The greenhouse operated successfully with neither heater nor forced draft ventilation until electric heaters were added for night use during the last two weeks of the test period.

The test units were 30 x 122 cm (1 x 4 ft) fiberglass boxes with 40 cm sides. A baffle plate was placed 10 cm from the end of the box. An exit port was placed between the baffle and end; sewage was introduced through a hose placed in the opposite end in plant material. A schematic diagram of the unit is shown in Figure 6.25. The unit sides were opaque, but plant material did not appear inhibited by lack of light since the plants extended well above the units. Figure 6.26 shows napier grass about 2 m tall extending from the unit.

Three units were connected in series to form a system. Screened raw wastewater was pumped continuously into the first unit by a Masterflex positive displacement pump. Influent was obtained from a manhole immediately upstream of the primary clarifiers. Turbulence in the manhole insured a completely mixed, representative sample of raw influent. To guard against clogging the small diameter tubing with grass solids, a basket of window screening was placed around the inlet before lowering into the manhole. Thus the liquid level was allowed to rise in the first unit over a four-hour period, after which it was pumped out from the exit port and into the next unit. The second and third units were operated in a batch mode, the effluent from the second unit entering the third and the effluent of the third unit pumped to the primary clarifiers of the treatment plant. Centrifugal pumps were used to transfer the flow between units and dispose of effluent. These pumps were controlled by three independent 24-hour timers which were operated synchronously. Ball valves were used to control the pumping rate between units to effect a smooth transfer of the contents within the 15 minute "in" cycle allowed by the timers. A schematic diagram of the system is shown in Figure 6.27. The time cycle of operation is noted on this figure. A picture of the shelter and enclosed units is shown in Figure 6.28.

Sewage was sampled as it entered the first unit and as it left the third unit. A proportional sampler was devised to collect a continuous sample from the effluent (shown in Figure 6.28). Although the pumping system devised for this experiment worked accurately and reliably, it was a

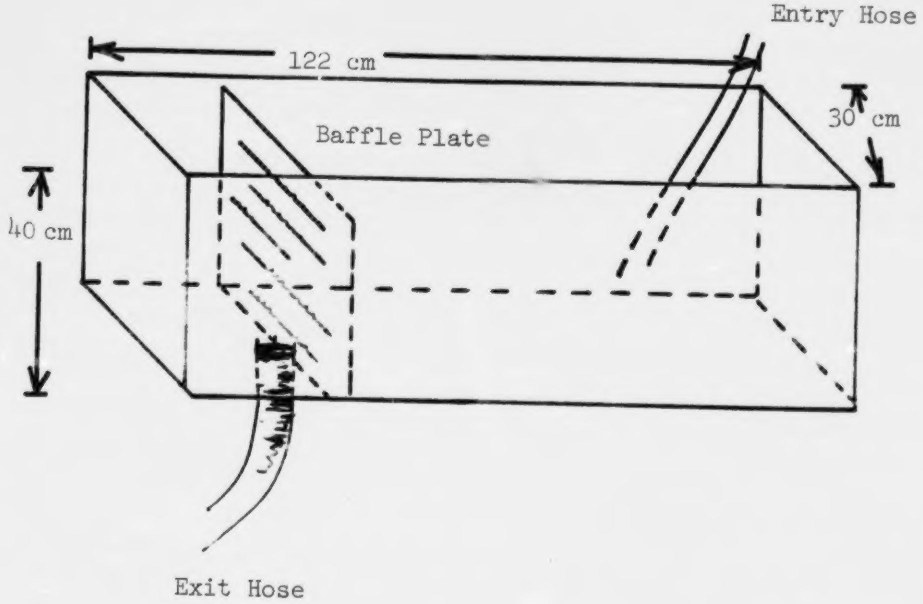


Figure 6.25. Test unit used in the high loading rate experiments using domestic sewage at the Cayuga Heights treatment plant.

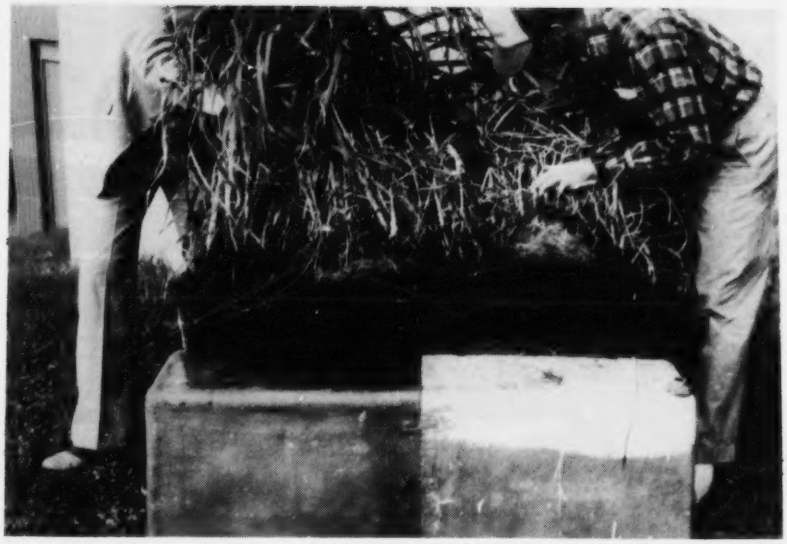


Figure 6.26. Napier grass used in high loading experiments at the Cayuga Heights treatment plant.

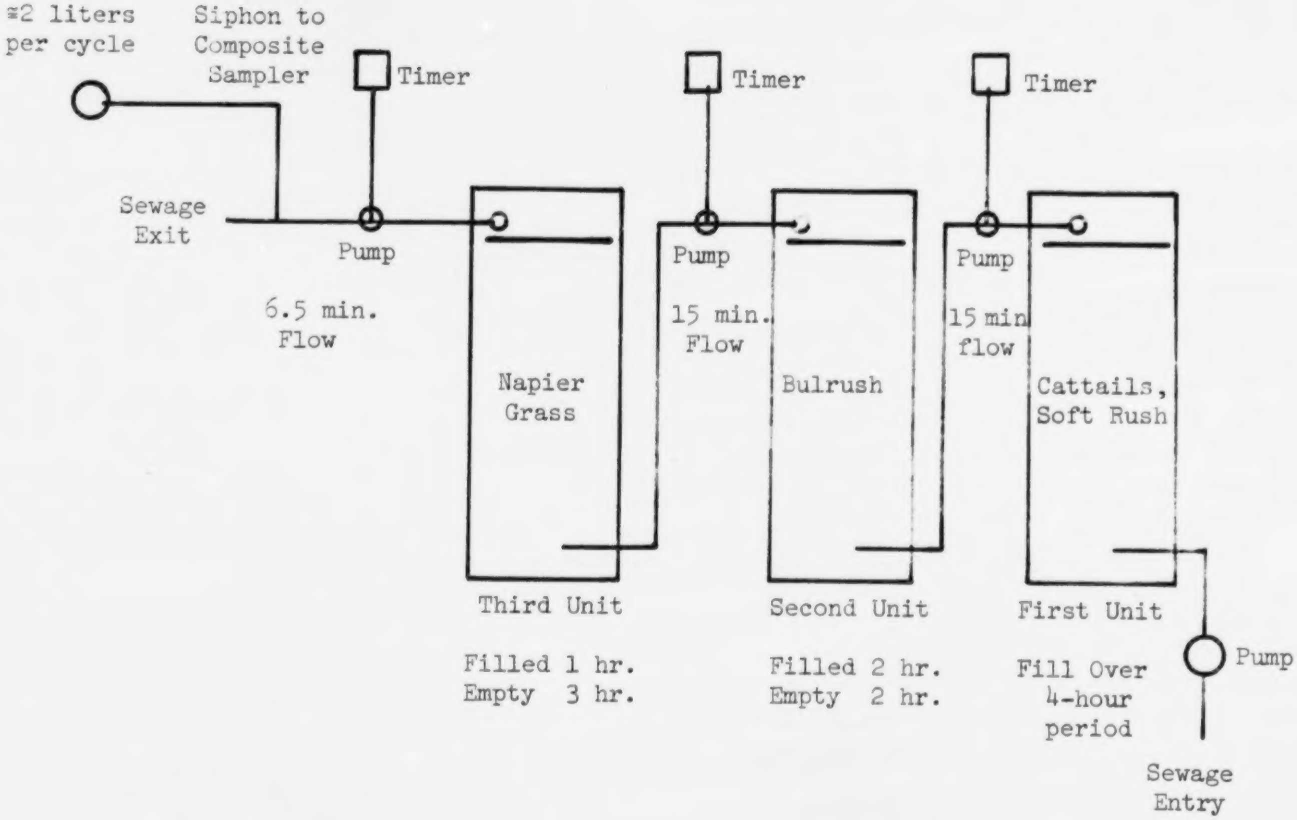


Figure 6.27. Schematic diagram of experimental system used for high loading rate experiments at the Cayuga Heights treatment plant.

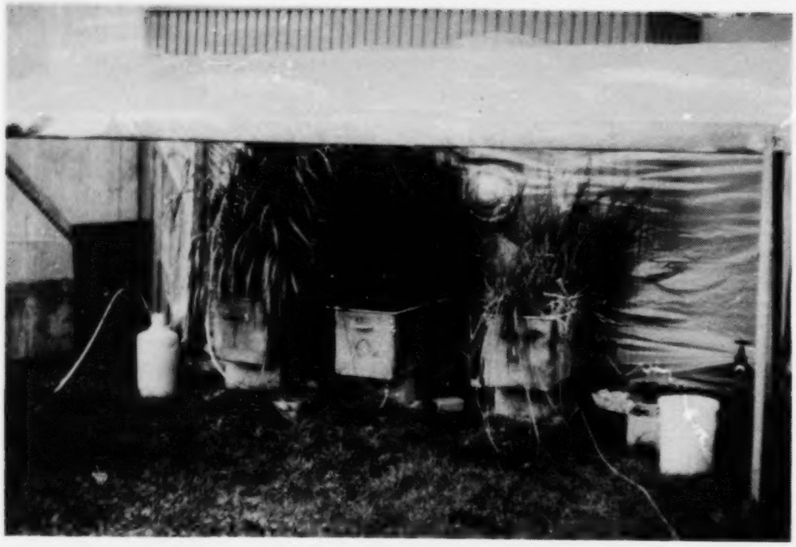


Figure 6.28. Plastic shelter and enclosed units at the Cayuga Heights, New York, treatment plant.

compromise between the ideal of moving wastewater instantly and without disturbance from tank to tank, and the reality of working within the constraints of time with readily available materials. The use of high speed centrifugal pumps did produce some disturbance within each unit and may have caused some change in solids properties. It is felt that a design which could avoid rapid handling of the wastewater at any point in the system would provide for intermediate sampling and a more realistic view of actual system capabilities. Such a system might employ timer-actuated gates or valves and gravity flow. Plants for these experiments were chosen from among those that appeared to thrive in a sewage environment (as demonstrated in experiments at the Hanover greenhouse). The first unit was filled with a mixture of cattail and soft rush, the second with bulrush and the third with napier grass. All plants were cut to a height of 30-40 cm above the roots and transplanted from Cornell greenhouses to the site. They were not cut again during the test period. Napier grass was placed in the last unit and provided with the greatest proportion of aeration time (three hours out of four) because previous experience had shown it to be susceptible to injury due to waterlogging. The napier grass performed extremely well, however, under these conditions. Bulrush was also well adapted and flourished under the conditions of the test. The cattails did not show as vigorous a response to the conditions. They could have been influenced by any number of factors, including the sewage characteristics and the fluctuating water level around their roots. Predation and disease were not a problem for any of the plants in this experiment.

After start-up in mid-July, the system was operated for four weeks at a loading of 20 cm/day. Loading was then increased to 30 cm/day for the remaining eight weeks of the test. Loading rates are summarized in Table 6.10.

The system was tested for soluble and total COD; suspended, total and settleable solids; and NH_4^+-N and TKN (organic N by difference).

TABLE 6.10. SCHEDULE OF EXPERIMENTAL CONDITIONS AT CAYUGA HEIGHTS

Dates From	To	Area Loading Rate cm/d	Weir Loading Rate m^3/m-d	Volume Wastewater Batch ℓ/4 hr cycle	Daily Volume ℓ/d
7/20/81-	8/14/81	20	0.74	37.7	226
8/15/81-	10/11/81	30	1.12	56.7	340

B.3. Comparison of Synthetic and Actual Domestic Wastewater

The synthetic wastewater used in this study was modeled after a medium strength domestic wastewater. There are several differences between this synthetic mixture and the wastewater on which it is modeled, and there are also other differences between the synthetic wastewater and the wastewater used at CRREL and Hanover.

Section A.1 describes the synthetic mixture used and lists the target concentrations of nutrients and contaminants. While it was possible to approach the chemical composition of sewage, there remained physical and biological differences between real and synthetic sewage. Essentially all of the constituents in the synthetic wastewater were dissolved, with only small amounts of suspended or colloidal material. In contrast medium strength sewage contains about 250 mg/ℓ of suspended and colloidal solids (Metcalf and Eddy, 1972). When solids were present in the synthetic sewage, it was usually caused by either (1) an inorganic precipitate which formed at high temperatures in the greenhouse, or (2) microbial matter produced in the feed concentrate container. The latter was suspected of being yeast since the feed acquired a yeast odor over the two or three days between new batches, and yeast extract was used as an ingredient. These solids never approached the concentrations of those in real sewage. With the exception of the aforementioned yeast, the synthetic sewage was devoid of any significant microbial population, which is in sharp contrast to real sewage. The NFT units' operation, however, did develop large populations of microorganisms in the root zone.

Comparisons of influent synthetic and real sewages used in this study are shown in Table 6.11. In comparison with the typical medium strength wastewater on which the synthetic sewage was based, the domestic sewage had lower concentrations of several constituents. Organics, phosphorus and solids in Hanover and CRREL sewage were less than typical values for sewage; and organics and phosphorus were less than those of synthetic sewage. Since the synthetic sewage contained few solids, the relatively low solids values of Hanover and CRREL were still much greater than those of the synthetic mixture. There were only small differences between Hanover and CRREL sewages, which is reasonable since CRREL draws its sewage supply from the Hanover system. While the Hanover system treats wastes from the entire town, the waste stream above CRREL includes only residential development plus intermittent accidental additions from the CRREL laboratories. As described in section 4.2.1, Hanover sewage was selected based on a number of factors suitable to the study.

Total and soluble biochemical oxygen demand (BOD) values in sewage were half of those in the synthetic substrate. Total and soluble chemical oxygen demand (COD) values were also less, but were greater than half. Part of this difference was due to the initial high target concentration of 400 mg/ℓ for the synthetic wastewater COD. For Phase 0 and the first condition of Phase 1, total and soluble COD averaged 403 and 392 mg/ℓ, respectively, while for the remainder of the study they averaged 249 and 236 mg/ℓ, respectively. These latter values are closer to those found in CRREL and Hanover sewage. Unlike domestic sewage, there was little difference between total and soluble BOD or COD since both were derived from a completely soluble substrate (sucrose). Small differences may reflect microbial growth in the feed.

Total nitrogen (N) concentrations were similar in the synthetic and real wastewaters, although the forms were different. Domestic sewage contained predominantly ammonium N (NH_4^+-N) whereas synthetic sewage N was added as urea. In nearly all cases, however, this urea N was rapidly hydrolyzed to NH_4^+-N. Real sewage rarely contained nitrate-nitrogen (NO_3^--N) and synthetic sewage often had traces of NO_3^--N, but never more than a few percent of total N.

Since phosphorus was added to the synthetic mixture as potassium phosphate salts, orthophosphate phosphorus (PO_4-P) represented total P.

TABLE 6.11. CHARACTERISTICS OF INFLUENT SYNTHETIC AND REAL SEWAGE
(All units are mg/ℓ except pH)

Variable	Synthetic Sewage Mean	Synthetic Sewage Std. Dev.	Real Sewage+ Mean	Real Sewage+ Std. Dev.
pH	6.9	0.3	7.3	0.3
COD	307	132	241	18
Soluble COD	288	98	175	11
BOD	186	26	103	29
Soluble BOD	169	23	80	5
TOC	------	------	101	10
Total N	35.7	8.9	36.9	10.6
Total Soluble N	35.4	9.3	-----	----
Total P	------	------	6.9	1.6
Ortho P	13.8	3.4	5.7	2.0
Soluble Ortho P	13.5	3.1	-----	----
Cd	0.08	0.04	-----	----
TS	492	180	-----	----
TVS	296	141	-----	----
TSS	5	3	71	38
VSS	3	2	61	28

+Average values of CRREL and Hanover primary settled sewage.

Total P of synthetic sewage was about twice that of the real sewage and greater than double the real sewage PO_4-P.

As noted earlier, Hanover and CRREL total and volatile suspended solids (TSS and VSS) were lower than typical values for sewage, while TSS and VSS in the synthetic sewage were virtually absent.

C. TESTING APPROACH

C.1. Parameter Evaluation

The primary procedure used in this project was to subject various plant species, primarily reed canary grass, to different applications of sewage or synthetic wastewater and measure both treatment efficiency and plant response. Many different flow rates were used. In continuous application systems, the flow rate is proportional to both the system area and the required area loading rate. For example, to load a 9.3 m^2 system with 10 cm of sewage per day requires a continuous application of 0.65 ℓ/min; loading a system with 20 cm/day or using a system of 18.6 m^2 at 10 cm/day would require twice the continuous application rate. These area loading rates are the primary references to loading conditions examined in this project.

Intermittent applications of sewage were used when it became apparent that long periods of submergence might damage the plants. To describe conditions tested under these intermittent loadings, the primary reference remained the equivalent depth of sewage over the system's area over a 24-hour period. Thus, a loading of 10 cm/day represents the same volume of sewage when applied to a single size system, regardless of application mode; for a 9.3 m^2 system this is 936 ℓ/day. Intermittent applications are described by the length of time sewage is applied and the length of resting period between applications. The instantaneous flow rate during application periods is then the flow rate of the continuous application divided by the fraction of time sewage is actually applied. Another way to view this is that the daily loading is condensed into a shorter application time, and instantaneous flow rate is increased correspondingly.

C.2. Season, Temperature and Environmental Controls

Nutrient film pilot systems were operated year-round, and this presented wide variations in greenhouse conditions. Both Ithaca and Hanover have short and relatively dark, overcast days in winter, with very cold outside air temperatures. In contrast summer days are long and warm, although Ithaca in particular is often overcast. No auxiliary lighting was used to lengthen photoperiod in the greenhouses. Electric heaters were used to maintain night temperatures at a minimum of 15°C. In spring, summer, and fall, ventilation fans were used to cool greenhouses when the temperature exceeded 25°C, although temperatures of 37°C were attained on some hot, sunny days.

Continuous temperature and humidity recorders were placed in each greenhouse, and incident solar radiation was measured at the Cornell Atmospheric Sciences Laboratory and at the CRREL weather station.

C.3. Test Parameters and Duration

Over the course of pilot scale experiments the loading rate varied from 4 to 40 cm/d, and most conditions tested were in the vicinity of 10 cm/d. Tables 6.12 and 6.13 summarize the schedules of the pilot scale systems for synthetic and domestic sewages, respectively. In addition to varying the daily loading, the method of application (continuous or intermittent) was also varied. Specific information on intermittent loadings is shown in sections A.2.b., B.1.b and B.1.d. As the project progressed, larger (longer) systems were used to estimate pollutant and nutrient removal over a range of root zone conditions. This increasing size culminated in the three-part systems at both Cornell and Hanover developed in the late stages of the project. Reed canary grass was the primary test species for first part of the project, while in later stages a varied collection of plants was used.

TABLE 6.12. TEST PARAMETERS AND DURATION OF THE CORNELL PILOT SCALE SYSTEMS USING SYNTHETIC SEWAGE

Dates		Daily Loading Rate		Application Mode	Flow Rate During Application	System Area	Plant Species
Start	End	cm/d	m^3/m-d		ℓ/m	m^2	
12/ 6/79-	1/ 2/80	10	1.24	Continuous	0.66	9.3	Canary grass
1/ 3/80-	1/27/80	10	1.24	Intermittent	2.6	9.3	Canary grass
1/28/80-	2/20/80	10	1.24	Intermittent	5.2	9.3	Canary grass
2/21/80-	3/17/80	10	1.24	Intermittent	2.6	9.3	Canary grass
3/18/80-	5/11/80	5	0.62	Continuous	0.33	9.3	Canary grass
5/12/80-	6/17/80	10	1.24	Continuous	0.66	9.3	Canary grass
6/18/80-	7/ 3/80	5	0.62	Continuous	0.33	9.3	Canary grass
7/ 4/80-	9/ 8/80	20	2.49	Continuous	1.3	9.3	Canary grass
9/ 9/80-	10/15/80	10	2.49	Continuous	1.3	18.6	Canary grass
10/16/80-	10/31/80	20	4.98	Continuous	2.6	18.6	Canary grass
11/ 1/80-	2/ 6/81	15	3.74	Continuous	1.0	9.3	Canary grass
2/13/81-	3/14/81	7	2.49	Continuous	1.3	27.9	Phragmites Cucumber Canary grass
4/16/81-	5/10/81	10	3.74	Continuous	2.0	27.9	Cattail/bulrush Phragmites Canary grass
5/11/81-	6/10/81	20	7.47	Intermittent	7.9	27.9	Canary grass
6/11/81-	7/ 1/81	40	14.94	Intermittent	16	27.9	Canary grass
7/ 2/81-	7/30/81	7	2.49	Continuous	1.3	27.9	Canary grass
7/31/81-	8/21/81	10	3.74	Intermittent	3.9	27.9	Canary grass

TABLE 6.13. TEST PARAMETERS AND DURATION OF THE CRREL AND HANOVER PILOT SCALE SYSTEMS USING DOMESTIC SEWAGE

Dates		Daily Loading Rate		Application Mode	Flow Rate During Application	System Area	Plant Species
Start	End	cm/d	$m^2/m\text{-}d$		ℓ/m	m^2	
11/16/79	12/ 2/79	5	0.62	Intermittent	-----	7.4	Canary grass
12/19/79	12/27/79	4	0.48	Intermittent	1.2	7.4	Canary grass
12/31/79	1/11/80	10	1.25	Intermittent	3.2	7.4	Canary grass
1/14/80	1/18/80	10	1.25	Intermittent	1.6	7.4	Canary grass
1/19/80	1/30/80	10	1.25	Intermittent	3.2	7.4	Canary grass
1/31/80	2/ 8/80	5	0.62	Intermittent	3.2	7.4	Canary grass
2/ 9/80	2/13/80	20	2.48	Intermittent	4.2	7.4	Canary grass
2/15/80	4/11/80	5	0.62	Intermittent	3.2	7.4	Canary grass
4/12/80	6/13/80	10	1.24	Intermittent	3.2	7.4	Canary grass
6/14/80	6/30/80	20	2.48	Intermittent	3.2	7.4	Canary grass
2/13/81	3/20/81	7	2.48	Continuous	1.3	27.9	Phragmites Cucumber Canary grass
4/13/81	5/ 8/81	10	3.74	Intermittent	3.9	27.9	Cattail/bulrush Phragmites Canary grass
5/ 9/81	6/ 3/81	20	7.47	Intermittent	7.9	27.9	Canary grass
6/13/81	8/21/81	5	1.87	Intermittent	2.0	27.9	Canary grass

C.4. Loading Rate Characterization--

There are several parameters that can be used to describe loading rates to an NFT unit. Three of them are described here. They are the area-volume parameter (the depth of liquid added per unit area per day, $cm/m^2\text{-}d$ or cm/d), the weir parameter (volume applied per unit width of system, $m^3/m\text{-}d$) and the retention time parameter (hydraulic retention time, min). The first two can be strictly operator-controlled, while the third can be variable depending on specific conditions present in the system and the length of the unit.

One way of describing a loading rate is to determine the equivalent depth of wastewater applied to an area. For example, if a cubic meter of wastewater is applied to an area of 50 square meters, the equivalent depth added is two centimeters. When a time dimension is added, the loading regime is completed. This loading rate parameter was originated in land application work, where land areas were used in various capacities to treat wastewater. As in land application systems, the methods of applying the wastewater and the system configurations of NFT systems can vary widely.

The depth added parameter is independent of the velocity of wastewater through the system. Velocity is determined by the rate at which wastewater enters the system during operating cycles and the slope of the units comprising the system.

From this parameter upper and lower limits to loading can be estimated. The lower limit must be high enough that water can flow through the entire system after taking evapotranspiration into account. Also, a low flow must be capable of supplying sufficient nutrients to plants and associated growth in the root zone. Generally, low flow rates will not be used in NFT systems since their use increases the area requirements of the system. However, they may be used to achieve efficient nutrient removals and thus a high quality effluent. Upper limits can be defined by desired effluent quality, with respect to BOD, SS and nutrients. Just as plants are limited in their ability to take up nutrients, the root zone, with its associated organisms, is limited in its ability to assimilate carbon and nutrients and to trap solids. Nutrient uptake is generally proportional to the area, while SS treatment depends on other factors (depth and velocity).

Another way of expressing loading rate to an NFT system is the loading per unit width of the unit, typically having units of $m^3/m\text{-}d$. This parameter which originated in overland flow land application describes the volume of water crossing the weir boundary into the system. This parameter is independent of the length of the units, unlike the area-based parameter which is dependent on length and width. It is useful in design where the length of a unit is fixed. Typical loading rates applied in overland flow treatment are less than 1.0 $m^3/m\text{-}d$ (USEPA, 1981).

Since many physical, chemical and biological pollutant control processes are time dependent, it may be useful to describe loading rates in terms of contact time of wastewater in the system. Hydraulic retention time (HRT) analyses determine the amount of time water resides in the system. Given the flow rate of water through a system, the volume of a system can be calculated as

$$V = (HRT)\,(Q) \tag{6.2}$$

where V = volume in ℓ
HRT = retention time in min. and
Q = flow in ℓ/min.

Since NFT units have open tops and flow is by gravity, much variation in water depth, volume and residence time is possible due to differences in the root zone condition.

Unlike the first two parameters described, HRT is not directly operator controlled. Areal and weir rates are adjusted where wastewater enters the system and can be controlled fairly precisely. Retention time can be estimated from the water depth and flow rate, or from empirical experience, but the exact determination requires experimentation. Although HRT may be known exactly at some point in time, it may change over the course of an experimental period due to changes in the root zone (clogging, flushing, growth, etc.).

Throughout this report, loading rates are referred to by the area-depth parameter because different size systems were used and this parameter was easily calculated, unlike the HRT parameter.

Comparisons between the three loading rate parameters are shown in Table 6.14. The area and weir loading rates are proportional within each size of unit tested. As the surface areas of the units are increased, the width is held constant and the length is extended (as described in section 6.a.2.b.). Thus the area loading rate (and the retention time) can be held constant, but the weir loading rate will increase for a longer unit. While the area rates give a better indication of the volume of water applied to the units, the weir rates give an indication of the velocity of the water through the units. Within each area loading rate, the water velocity increases as the unit is lengthened.

TABLE 6.14. COMPARISON OF LOADING RATE PARAMETERS FOR SYNTHETIC SEWAGE

System Size		Loading Rates		
Area (m^2)	Length (m)	Area cm/d	Weir $m^3/m\text{-}d$	HRT[1] min
9.3	12.2	5.1	0.62	52
		10.2	1.24	73
		20.3	2.48	40
		30.5	3.16	32
		40.6	4.95	----
18.6	24.4	5.1	1.24	----
		10.2	2.48	172
		20.3	4.95	114
27.9	36.6	5.1	1.86	----
		6.9	2.51	367
		10.2	3.72	105[2]
		20.3	7.43	109[2]
		40.6	14.86	91[2]

[1] Selected HRT values for 9.3 m^3 system; data from unit #3 in Bracehouse.
[2] System operated on intermittent loading condition.

The retention time parameter varies inversely with the area and weir parameters. As increasing amounts of wastewater are applied to a unit, the residence time of that water in the unit decreases. This relation is not exact because other factors in addition to influent flow rate come into play. The depth of wastewater in the units increases with flow since the water is forced to flow around or even over the root mats. This increases the volume of the system and thus increases retention time above that which would be predicted by flow alone. Also biomass in the root zone tends to increase over time due to root growth, sloughed plant parts, precipitate accumulation and microbial growth. This additional matter can clog pathways through the root mat, forcing wastewater to find new routes. As this process proceeds, the root zone may become sufficiently clogged to force flow above the root mat. Conversely, as the flow rate is increased, the water velocity may reach a critical value at which particulate matter is dislodged in the flow and removed from the unit.

In testing some conditions the systems were operated on an intermittently loaded schedule. During these conditions the retention time was less than when systems were operated under continuous loading since wastewater was added up to four times as rapidly as in the continuous operation. Figures 6.29 and 6.30 show hydrographs for the synthetic sewage pilot scale units operated at 10.2 and 20.3 cm/d loadings, respectively. These determinations were made by the bucket and stopwatch method. A large block of sewage (the influent to the first unit shown as curve A) enters the system and passes through the first and subsequent units rapidly. The influent sewage displaces sewage in the system as its momentum moves through; the sewage that runs off the first, second and third units (shown as curves B, C and D, respectively) may have entered the system at an earlier application period. Both loading schedules showed rapid movement of the water in the system. From the tracer studies it appears that the system holds a considerable amount of water since peaks immediately following the application peak did not contain large quantities of the tracer. Rather, the bulk of water with the added tracer displaced other water in the system and the introduced water did not leave the system until it was displaced by subsequent additions.

From water depth measurements in the units it was clear that the volume contained within the units varied considerably depending on root conditions. Table 6.15 shows volumes in the various units determined from mean depth. Unit #1 in Hanover was sloped at 0.5% during the 6.9 cm/d condition, which resulted in a volume that was considerably less than that of the Cornell unit, which was level. The plants used in each unit were changed between the 6.9 and 10.2 cm/d conditions. As shown in the table, units 1 and 2 contained phragmites and cucumbers, respectively, in the 6.9 cm/d condition, while they contained cattails and bulrush in unit 1 and phragmites in unit 2 for subsequent conditions. For some loading conditions of 10.2 cm/d or greater, an intermittent loading regime was used. The intermittent loadings may have produced shorter retention times than if the system had been loaded continuously.

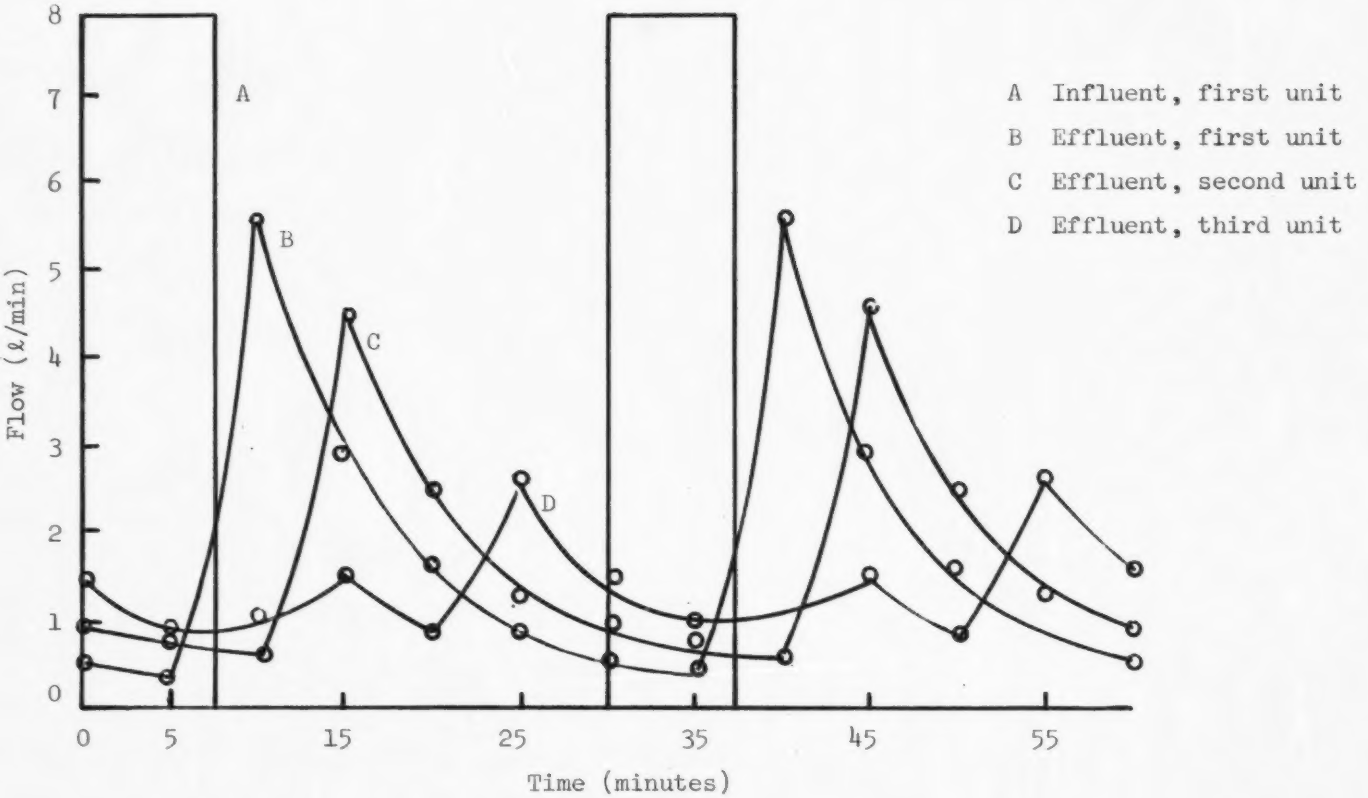


Figure 6.29. Hydrograph for 36.6 m Bracehouse pilot system on 4-27-81 (10.2 cm per day, loaded during first 7.5 minutes of each half hour). These are direct flow measurements over time for synthetic sewage entering and leaving the system, and at two intermediate points.

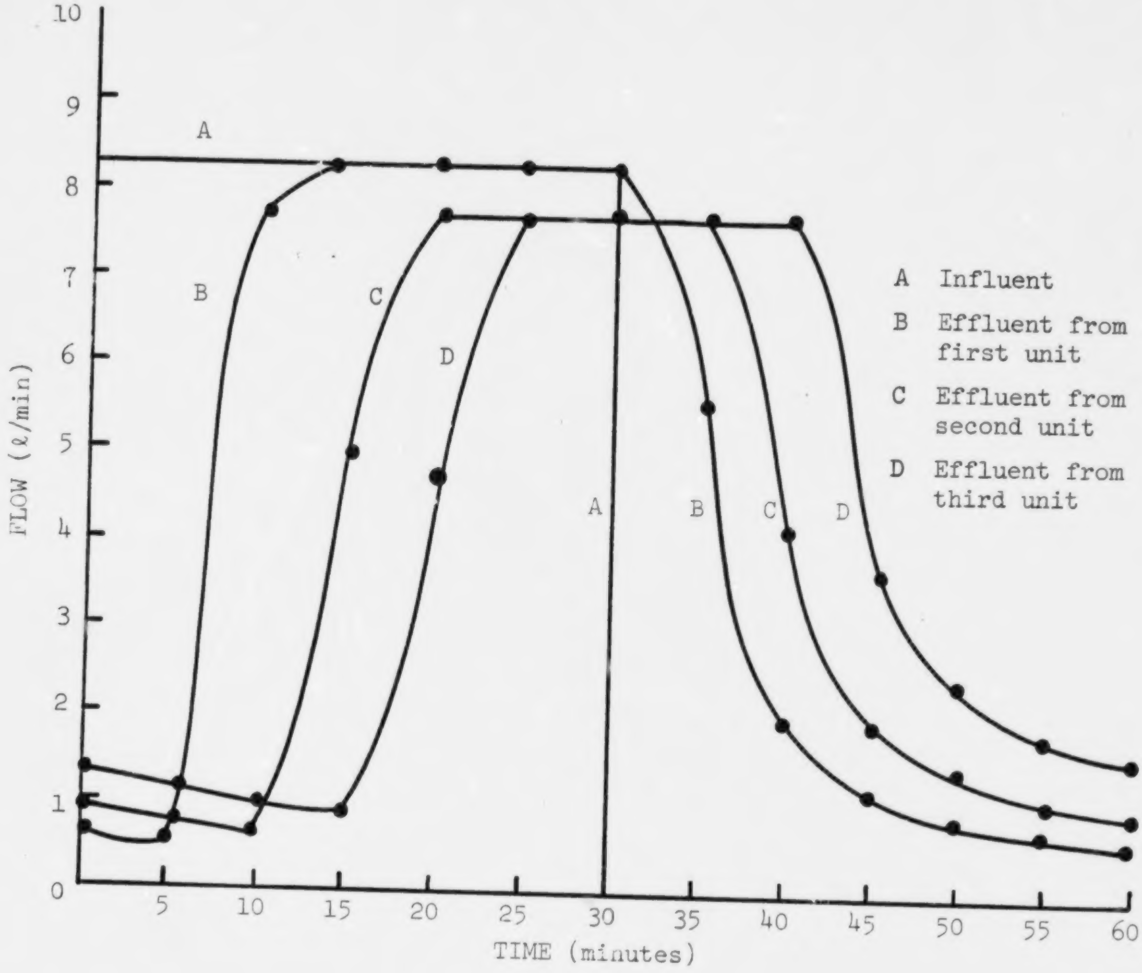


Figure 6.30. Direct measurement of flow entering and leaving various units in Bracehouse system on May 27, 1981. Flows at this condition, where synthetic sewage was applied for alternating 30-minute periods, were pulsed much more distinctly than those where the influent flow was smaller and more frequently applied (Figure 6.28).

TABLE 6.15. TYPICAL HYDRAULIC CHARACTERISTICS OF A 36.6 m LONG (27.9 m^2) PILOT SCALE NFT UNIT AS ESTIMATED FROM WATER DEPTH MEASUREMENTS DURING OPERATION OF THE UNIT

Site	Area Loading Rate cm/d	Unit Volume, liters				Average Flow ℓ/min	Instantaneous Flow During Influent Application Cycle
		1	2	3	Total		
Cornell (Synthetic sewage)	6.9	242 (P)*	37 (C)	251 (R)	530	1.33	1.33
	10.2	186 (B)	84 (P)	233 (R)	503	1.97	7.88
	20.3	344 (B)	233 (P)	344 (R)	921	3.93	15.72
	40.6	456 (B)	419 (P)	363 (R)	1238	7.87	15.72
Hanover (Domestic sewage)	6.9	167 (P)	37 (C)	149 (R)	353	1.33	1.33
	10.2	158 (B)	102 (P)	188 (R)	548	1.97	7.88
	20.3	251 (B)	140 (P)	307 (R)	698	3.93	15.72

*Plant species in each unit shown in parentheses. (B=Cattail/Bulrush; P=Phragmites; C=Cucumber; R=Reed Canary Grass)

Several generalizations can be made in regard to the volumes contained in the various units. In almost all cases the volume increased with increasing flow rate. Within each species tested the volume of water contained in the root zone increased with increased loading. The exception to this is phragmites, which contained a larger volume in the first unit than it did in the second. (As noted earlier, the first units were level or only slightly sloped, unlike the second or third units, which were sloped at 2%.) As the flow rate was increased, the surface level rose until flow through the system was equalized.

With regard to phragmites units, it appears that the slope of the units had a large effect on the volumes contained. At Cornell, phragmites in unit 2 contained less than half that contained when it was in unit 1, despite the larger flow at the 10.2 cm/d condition. Similarly, at Hanover the volume was reduced 40% by placing phragmites in the second position, again despite the larger flow.

The extent of the interwoven root mat affected the volume of the system in two ways. Plant species differ in root mass and form with some plants, such as canary grass, having many small roots while others have large rhizomes with fewer small roots. The root mat of some plants increased considerably over the course of experimentation, and this contributed to the amount of trapped water. The canary grass units usually contained a large volume of solution relative to other species, even despite its 2% slope. The mat of fine roots maintained a uniform depth across the units in contrast to plants with fewer larger roots or rhizomes which channeled or distributed solution unevenly. The largest root system grown during the course of pilot scale experiments was the phragmites stand in unit 2, particularly the stand at Cornell. The root system of napier grass was more extensive than that of phragmites, but napier grass was not used in pilot scale systems. This large root mat is reflected in the large volumes this unit held.

Hydraulic retention times for the large pilot scale units are shown in Table 6.16 for the different conditions tested. Some of the same factors which affect volume also appear to affect retention time. For example, canary grass usually had a large HRT relative to other units, particularly in the Hanover unit. The HRT was generally reduced at higher loading rates, as expected, and was also less when the application period was shortest (10.2 cm/d condition). Data of particular interest in Table 6.16 are the sewage HRTs at the 6.9 cm/d condition. Over a short period, HRT increased by 61 minutes; since plant growth in mid-March was not rapid, it was hypothesized that the increased HRT was due to trapping of solids. Cucumbers had only a small root mat which did not cover the unit's surface; any increase in the HRT of this unit was caused by sedimentation or attachment of particles or microbial growth and a resulting increase in volume of the unit.

In the Cornell pilot system, several observations can be made. In general, HRT did not change a great deal from the 10.2 cm/d loading to the 40.6 cm/d loading. This is due in part to the higher volumes contained in the units at successively higher flows and the increasing maturity of the units with increasing loadings. The phragmites unit in the 40.6 cm/d loading appears inconsistent with this observation.

D. PLANT CONSIDERATIONS

D.1. Plant Selection Criteria

This section describes the criteria on which plant species were selected for study and the methods and places of culturing and collection. A wide variety of plants was tested, often under deficient nutrient and light conditions similar to those that would be experienced in a treatment system. Although many interacting variables affected the plants, some recommendations on the suitability of species for NFT use were possible.

While horticulturalists have used the NFT for plant culture since 1975 (Cooper, 1975), adapting this system to treating sewage requires some modification. Compared to hydroponic culturing solutions, sewage is low in nutrients and dissolved oxygen, and contains solid matter which tends to accumulate in the root zone. In addition to surviving these adverse conditions, plants must improve the water quality by taking up nutrients and contaminants and provide the root zone surface upon which microorganisms may grow. The overall list of the most favorable characteristics in plants is

TABLE 6.16. COMPARISON OF DETENTION TIMES (IN MINUTES) IN 27.9 m^2 PILOT SCALE UNITS OPERATING AT DIFFERENT CONDITIONS WITH REAL AND SYNTHETIC WASTEWATER

Area Loading Rate cm/d	Date	Synthetic Sewage Units Unit 1				Date	Real Sewage Units Unit 1			
		1	2	3	Total		1	2	3	Total
5.1						8/ 6/81	71 (B)	83 (P)	84 (R)	238
6.9	3/ 3/81	121 (P)*	49 (C)	197 (R)	367	3/10/81	66 (P)	17 (C)	70 (R)	153
6.9						3/19/81	86 (P)	24 (C)	104 (R)	214
10.2	5/ 7/81	48 (B)	27 (P)	30 (R)	105	4/22/81	24 (B)	32 (P)	51 (R)	107
13.6						3/26/81	87 (P)	25 (C)	81 (R)	193
20.3	5/28/81	38 (B)	23 (P)	48 (R)	109					
40.6	7/ 2/81	44 (B)	9 (P)	38 (R)	91					

*Plant Species in Each Unit are shown in Parentheses (B=Cattail/Bulrush; P=Phragmites; C=Cucumbers; R=Reed Canary Grass).

shown in Table 6.17 and are described below. While possibly no species exhibit all these characteristics, many species show promise in several categories.

TABLE 6.17. FAVORABLE PLANT CHARACTERISTICS FOR TREATMENT OF WASTEWATER IN NFT SYSTEMS

A. Tolerance to adverse conditions, such as

Standing or flowing water
Anoxic conditions
Sludge buildup and clogging in root zone
Short photoperiods
Temperature extremes and fluctuations
Nutrient stress
Some degree of arthropod damage or disease

B. Good performance as a treatment medium and a useful crop

High nutrient uptake
High productivity
Extensive root, rhizome and/or shoot system
Production of a valuable commodity

C. Cultural considerations

Wide geographic availability
Easy and rapid propagation
Minimal maintenance
Not a pest species

Treatment of wastewater by using the nutrient film technique requires plants that can tolerate excessive water and low oxygen concentrations particularly for removal of gross pollutants such as BOD and SS. The plants in the system are intended to treat wastes by their uptake capabilities and by their root structure. A species that requires extreme aeration and frequent drying of the root zone is therefore of limited use. In nature, many plants (such as reed canary grass) are able to withstand the wet spring season without adverse effects and continual growth in the drier summer months. The usefulness of these plants depends on their ability to tolerate water throughout their life cycles. Other species (such as cattails and bulrushes) are able to tolerate continuous flooding and anaerobic root zones.

Typical sewage contains many constituents whose decomposition consumes oxygen. Under conditions of stagnant or slowly flowing sewage, chemical and biological processes are especially effective in depleting the dissolved oxygen supply. Since the treatment of wastewater with the NFT depends, in part, on these processes occurring in the root zone, plant species must be able to survive low dissolved oxygen concentrations. Most commercially grown plant species do not tolerate such conditions, and many designs of hydroponic systems include air spargers or other mechanisms for maintaining the D.O. near saturation. In commercial NFT systems reaeration is accomplished through the turbulence of the thin film. However, depletion of the oxygen due to decomposition with dissolved organic carbon is faster than the natural reaeration. While a reaeration step could be added to an NFT unit, it would be difficult and costly. Some plant species--those of interest for use in NFT systems--survive and grow quite well in anaerobic sediments possibly due to an ability to translocate oxygen downward through the plant tissue to the roots for respiration (Hutchinson, 1975).

The majority of the nutrients and carbonaceous material in sewage is in colloidal and particulate form rather than dissolved. The physical means to treat these solids in an NFT include sedimentation, filtration and adsorption, all of which result in material deposition in the root zone. Although this may provide material for anchoring the plant's roots, it is a highly carbonaceous mass that characteristically has no dissolved oxygen present and contains reduced materials. This mass may inhibit gas exchange to the roots and create an anaerobic sludge layer into which plant roots cannot penetrate. Plants with fine root hairs may suffer clogging from fine particles sooner than would plants with large roots or rhizomes.

Since the NFT is viewed as a year-round treatment system, plants are required that can grow, or at least remain viable, through the short daylight periods of winter. Ideally the plant would not go dormant, but would continue to grow year-round, taking up nutrients and extending roots. At a minimum the roots should provide a living surface to support physical, chemical and microbial processes. Photoperiod and light intensity, like temperature, are variables that can be operator controlled. The addition of lights can extend daylength or increase the light intensity, while black covers can simulate darkness. A number of plants, for example, chrysanthemum and poinsettia, are stimulated to flower under short day conditions and will not grow vegetatively. If flower formation is desirable during long day conditions, an artifically short day can be provided with a black cover. New cuttings need a long day to form a stem and leaves. This longer day can be artificially provided with artificial light. On the contrary, at higher latitudes the light intensity in winter is often not sufficient for adequate photosynthesis. To achieve good plant growth artificial lighting with high intensity lights is necessary. This is energy- and capital-intensive.

Temperature fluctuations in the form of excessive heat in summer and the lack thereof in winter may be stressful to plants. While the hypothesized NFT system includes a greenhouse covering for the plants, this provides both a help and a hinderance: it allows operation of the system through the winter but requires cooling in the summer. A cost-effective system must minimize the energy input for temperature maintenance. Also, since greenhouses with limited temperature control are subject to greater variations and fluctuations, the plants should be tolerant of considerable daily temperature fluctuation.

In contrast to a horticultural hydroponics system, a waste treatment NFT uses a fairly dilute nutrient solution. While the N-P-K ratio of a typical hydroponics solution is 200-40-100, the ratio of a medium strength sewage is 40-15-12. In addition, the nutrients in sewage may be in organic compounds that must be microbially degraded before nutrients are freed for plant uptake. The available nutrients then may be even lower than the low N-P-K ratio. While this low level of nutrients can support plant life, some nutrients such as potassium may be limiting in a sewage solution. Nitrogen in sewage occurs in the organic or ammonium form. The organic nitrogen is decomposed to ammonium. In recent years it has been shown for several crops that NO_3^--N is the preferable nitrogen form and that the ammonium ion can cause toxic effects when present in higher concentrations. This seems to be important in NFT systems (Langhans, personal communication; Massey and Winsor, 1980). Also, some micronutrients, such as sulfur, boron and iron, may be deficient and limit the growth of tomatoes and other plant species (Wallace _et al_., 1978).

Due to the adverse conditions for NFT plant production, less vigorous plants may be more subject to attack by parasites or disease than would vigorously growing plants. Because some levels of disease and pest infestations are to be expected in the NFT systems, effective methods of control requiring minimal labor should be developed.

Because one of the goals of NFT treatment is nutrient removal, high nutrient uptake by the plants is important. Plants with the capability of fast root growth and nutrient scavenging would not only remove nutrients from solution but would also be well suited in other ways such as providing increasing surface area for bacterial growth.

The production of a valuable plant end product would decrease the system's operating costs and demonstrate an additional value of the NFT treatment system. The production of flowers, for example, would generate an income to the system above and beyond the special handling costs involved. All plants grown in an NFT system would have some value as forages or biomass, but crops such as ornamental or medicinal plants would yield a much more valuable end product. The production of non-edible plants would be desirable because problems with toxic materials would be avoided.

Another desirable characteristic of NFT plants is that they would have a wide geographic availability. This would allow for more standardization of system designs and easier collection of material. A wide geographical distribution may also indicate that a plant is able to grow under a variety of temperature and light regimes, which is desirable for year-round NFT operation.

In addition to having wide tolerances, plants in the NFT that can be propagated quickly and easily would be highly desirable. If a species chosen has a short yet productive lifespan, it will need frequent replacement. For example, annuals such as Japanese millet grow to maturity in less than three months, at which time they require harvest and replanting. In contrast, perennial grasses which root quickly from cuttings can be propagated in a wastewater stream. A complicating factor in this comparison, however, is that species with lower economic value tend to be the easiest ones to propagate.

The last criterion is that plants selected should not be a pest species. Many plants have become pests by their introduction to new areas. Examples of these plants in the U.S. are kudzu, water milfoil and water hyacinth. A plant with the capability of rampant and damaging growth should not be introduced in an NFT system, regardless of the performance in the system (unless special precautions were taken to ensure the plant was contained in the system). Consultations with professional botanists should precede the use of non-native plant species in the system.

Since many different types of plants can be grown in NFT systems, there is a hierarchy of end uses of the plants. These uses can be ranked on the basis of end product value and also according to the number of possible end products. For example, many plants can be used as biomass, but a smaller number is available for food production. When one considers the number of species available for use in the NFT and their economic value, an inverse relationship between these two variables becomes evident (Figure 6.31).

Using plants for biomass production is the least valuable disposition of plant material. Essentially all plants grown could be composted or processed for energy recovery. Flower or ornamental crops could produce a significant income to the system, and concern for contaminant uptake would be minimal.

Many food and forage crops can be grown using NFT. During this project reed canary grass and other forage species have been grown successfully, and an elevated protein content has resulted in reed canary grass when grown in solution culture. Similarly many vegetable species have been grown successfully hydroponically. While food production may yield a larger income to the system than would biomass production, more stringent quality control requirements may be imposed on the system. For example, vegetables would need to be free of pathogens and heavy metals, which would necessitate extensive testing and possibly some pretreatment. In many cases the production of vegetables would not be an option.

Crops with very high value such as pharmaceutical herbs could also be grown in NFT, but the problems of quality control that would have to be solved would be significant.

For any crop the overriding criterion for its selection must be its ability to perform the wastewater treatment required. If a group of plants meets this requirement then plants can be selected based on other desirable characteristics or end products.

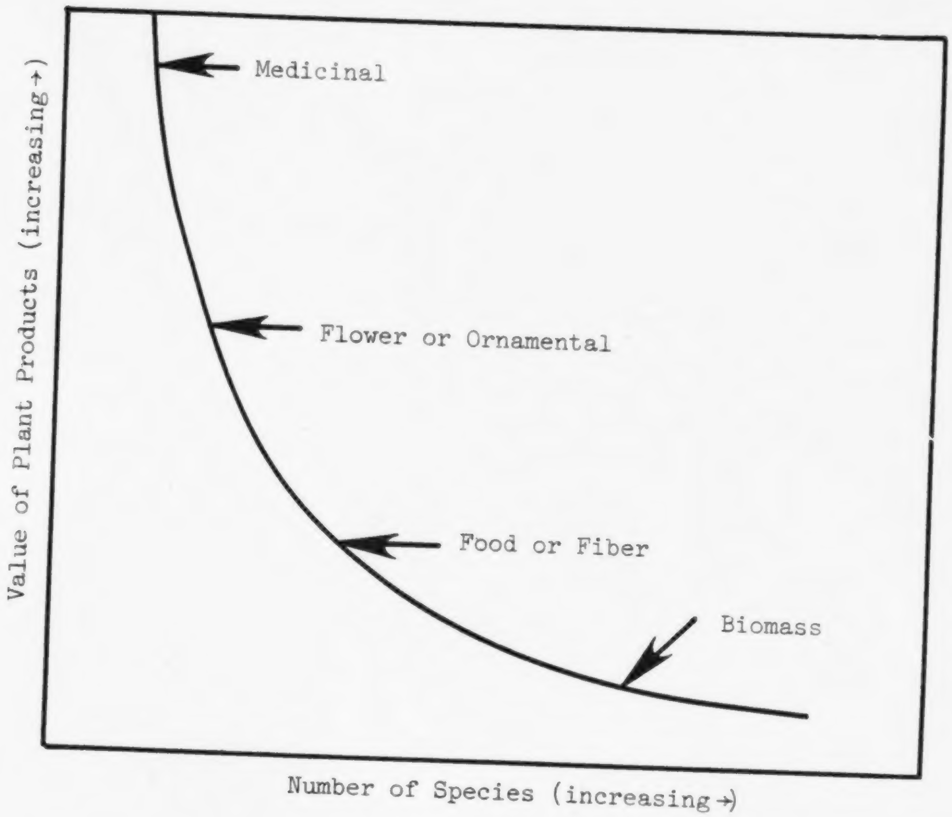


Figure 6.31. Relation between the number of species included in an end product and the relative value of that end product.

D.2. Species Tested

A number of emergent aquatic plants were selected for initial study. Plants that had performed well in commercial hydroponic systems were added after hardy plants were identified. These plants included both food and ornamental crops. Other plants were added to the test program on the basis of some known desirable characteristic. For example, napier grass grows very fast and propagates easily. The list of plants used in this study is shown in Table 6.18.

TABLE 6.18. PLANTS GROWN IN NFT UNITS OR EXAMINED FOR CULTURAL PROPERTIES DURING THE STUDY

Aquatic or wetland plants

Arrow arum (Paltandra virginica)
Big burreed (Sparganium eurycarpum)
Bristly sedge (Carex comosa)
Soft stem bulrush (Scirpus validus)
Burreed (Sparganium americanum)
Common cattail (Typha latifolia)
Japanese knotweed
  (Polygonum cuspidatum)
Lake sedge (Carex lacustris)
Lizard tail (Saururus cernuus)
Phragmites (Phragmites australis)
Soft rush (Juncus effusus)
Swamp loosestrife
  (Decodon verticillatus)
Woolgrass (Scripus cyperinus)

Dryland plants

Reed canary grass (Phalaris arundinacea)
Eastern cottonwood (Populus deltoides)
Napier grass (Pennisetum purpureum)

Vegetable or food plants

Blackberry (Rubus spp.)
Comfrey (Symphytam spp.)
Cucumber (Cucumis satiuus)
Japanese millet
  (Echinochloa frumentacea)
Sugar cane (Saccharum officinarum)
Tomato (Solanumlycopersicum)
Wheat (Triticun aestiuum)
Wild rice (Zizania aquatica)

Flowers

Chrysanthemum
Carnation
Fushia
Geraniums
Lantana
Marigold
Petunia
Rose
Strawflower
  (Helichrysum monstrosum)

D.3. Culturing Considerations

D.3.a. Obtaining Plant Material—

Following the selection of plant species, those available in nearby wetlands were collected. The majority of species were collected in late summer and fall of 1980. Reed canary grass was collected many times over the course of the project since it was a major test species. Similarly, large quantities of phragmites were collected in November 1980, and cattail and bulrush in March 1981 to plant in the pilot scale units. A typical stand of phragmites is shown in Figure 6.32.

The location and date of collection of the species that were collected are shown in Table 6.19. Plants were removed from their habitats using garden tools, transported in plastic bags and placed in NFT units. Any soil or dead growth that was collected with the plant material was removed at the greenhouse before the material was placed in the units. All species were placed in one or two of the three meter units in the Ken Post greenhouse, and large quantities of certain species collected were placed in the larger 6.1 meter units.

TABLE 6.19. COLLECTION DATA FROM WETLAND PLANTS GROWN IN THE NFT

Species	Propagation Type of Propagule	Location	Date
Arrow arum	entire plant	Montezuma Wildlife Refuge	9- 7-80
Big burreed	rhizome with shoot	Montezuma Wildlife Refuge	9- 7-80
Bristly sedge	sod	Cornell Agronomy ponds	8-28-80
Burreed	rhizome with shoot	Cornell Agronomy ponds	8-28-80
Common cattail	rhizome with shoot	Town of Dryden, NY	many
Japanese knotweed	rooting branch tips	Cornell University	6-15-81
Lake sedge	sod	Town of Dryden, NY	8-29-80
Lizardtail	rhizome with shoot	Montezuma Wildlife Refuge	9- 7-80
Phragmites	rhizome	Montezuma Wildlife Refuge	9- 7-80
Reed canary grass	sod	Cornell Agronomy ponds	many
Soft rush	entire plant	Cornell Agronomy ponds	8-28-80
Soft-stem bulrush	rhizome with shoot	Cornell Agronomy ponds	8-28-80
Swamp loosestrife	rooting branch tips	Montezuma Wildlife Refuge	9- 7-80
Woodgrass	sod	Cornell Agronomy ponds	8-28-80

The most actively growing or most viable plant parts were collected. Where plants reproduced vegetatively, those reproductive parts were collected. For species in which little vegetative spread occurred, the entire plants were harvested.

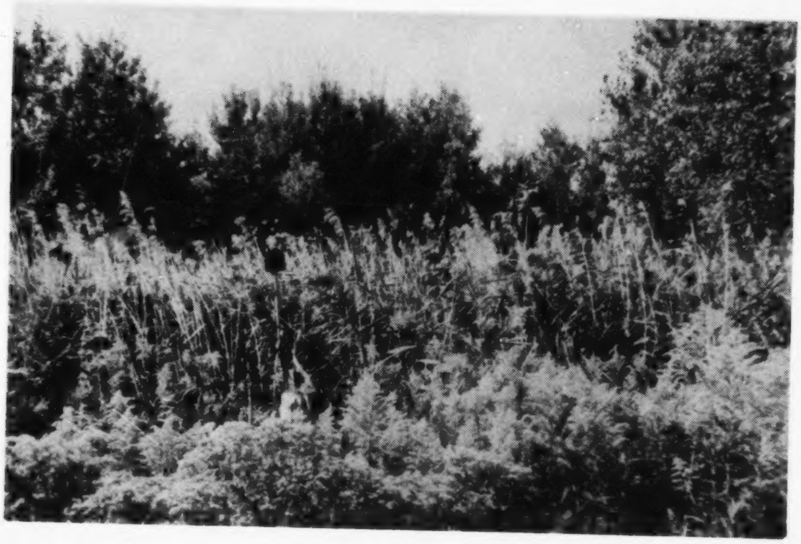


Figure 6.32. Stand of phragmites at Montezuma Wildlife Refuge

In addition to those plants harvested intentionally, seeds, roots or viable parts of other plants were inadvertantly collected. All of these species grew to some extent with the primary species in the NFT unit and were monitored. A list of these volunteer plants is presented in Table 6.20.

TABLE 6.20. VOLUNTEER SPECIES WHICH SURVIVED TRANSPLANTING WITH OTHER WETLAND SPECIES

Bedstraw (Galium sp.)
Bittercress (Cardamine pennsylvanica)
Buttercup (Ranunculus sceleratus)
Duckweed (Lemna minor)
False nettle (Boehmeria cylindrica)
Jointed rush (Juncus articulatus)
Purple loosestrife (Lythrum salicaria)
Water parsnip (Sium suave)

Several commercially grown plant species were propagated from seeds, stem cuttings and root cuttings. These plants, along with their sources and transplanting form, are given in Table 6.21. In general, seeds were not germinated directly in the NFT because they would either be washed away or fail to develop a supporting root system. Figure 6.33 shows one attempt to root canary grass in stream by using capillary matting. Seeds of reed canary grass and Japanese millet were germinated on "bubble plastic." Most other seeds were germinated in "Jiffy 7" peat pots in a misting house.

These are small pots which consist of dried compressed peatmoss. They were expanded with water, and seeds were planted in premade holes in the tops. Periodic misting (approximately 10 seconds every 10 minutes) kept seeds from drying out without depriving them of oxygen. Flowers from Horticulture and Ornamental Floriculture were started as cuttings which were rooted in peat pots on a mist table. Other flowers and vegetables were obtained in plant flats or pots containing some potting soil. Before these plants were placed in the NFT units, the soil was removed from the roots. Attempts to germinate seeds in peat pots placed directly in NFT units were unsuccessful; apparently roots could not grow into the water-saturated peat. Some plant cuttings devloped rapidly in the nutrient film. Napier grass and sugarcane are two such species whose cuttings (stem sections with one or more nodes) grew to new plants directly in the nutrient solution (see Figure 6.34). Subsequent cuttings from the resulting napier grass stand were successfully propagated in both nutrient solution and sewage.

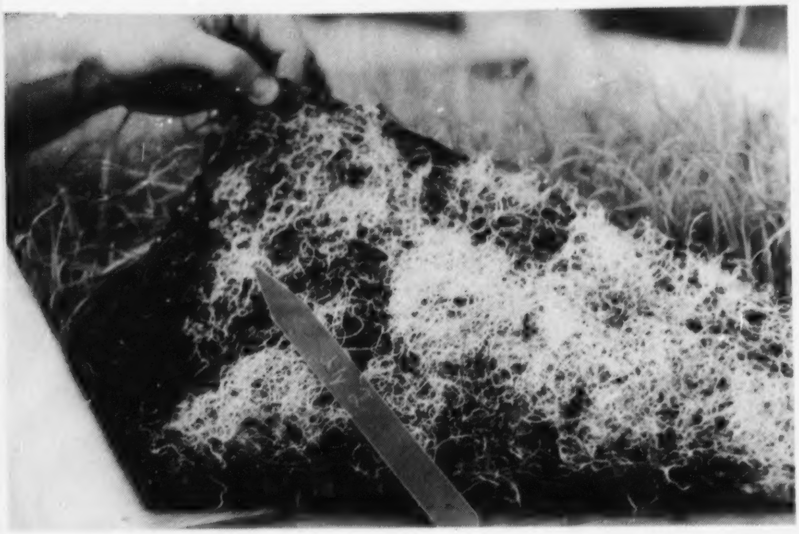


Figure 6.33. White canary grass roots forming a root mat below capillary matting used in seeding trials.

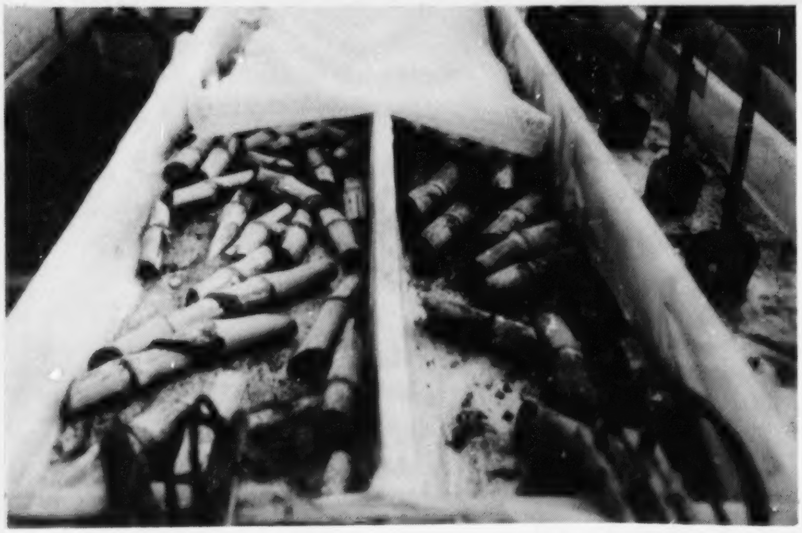


Figure 6.34. Napier grass, sugar cane, and cottonwood cuttings (left to right) after placement in the NFT 3 meter units. The bubble pack plastic was used to partially control algae. Cottonwood cuttings are in "Jiffy T" peat pots.

TABLE 6.21. SOURCES AND PROPAGULES OF COMMERCIAL PLANTS GROWN IN NFT UNITS

Form	Plant	Source
Seed	Cucumbers	Bruinsma Seed Co., N. Ridgeville, OH
Seed	Reed canary grass	Bruinsma Seed Co., Mecklenburg, NY
Seed	Wild rice	Kester's Wild Game Food Nurseries, Inc. Omro, WI
Seed	Millet	
Seed	Strawflowers	Geo. W. Park Seed Co., Inc. Greenwood, SC
Seed	Chrysanthemums	
Cuttings	Napier grass	Univ. of Puerto Rico, Rio Piedras, PR
Cuttings	Sugarcane	
Cuttings	Cottonwood	Boyce Thompson Inst. for Plant Research
Rooted cuttings	Blackberries	Agway, Inc., Ithaca, NY
Plants	Geraniums	J. Bartlett's, S. Sudberry, MA
Plants	Fuchsia	
Plants	Lantana	
Plants	Geraniums	George's, Newark Valley, NY
Plants	Cucumbers	George's, NH
Plants	Tomatoes	
Plants	Chrysanthemums	Cornell Dept. of Horticulture and Ornamental Floriculture
Plants	Carnations	
Plants	Roses	
Plants	Petunias	
Plants	Marigolds	Kings Dept. Store, W. Lebanon, NH
Tubers	Comfrey	backyard plant - E. Falmouth, MA

D.3.b. Growing Plant Material--

Carbon-free nutrient solutions were used to grow plants in Ken Post greenhouses at Cornell, whereas sewage was used for propagation in the Hanover, New Hampshire, greenhouse.

The nutrient solution used in Ken Post was composed of the following ingredients:

Peter's Hydrosol soluble fertilizer
Calcium Nitrate
Chelated iron

The hydrosol fertilizer had a low N:P ratio compared to sewage, so additional nitrogen was added as $Ca(NO_3)_2$. The iron was added as a supplement to the fertilizers since many plants, particularly reed canary grass, had shown Fe deficiencies earlier in the study. The strength of the solution was maintained by monitoring the conductivity and subsequent nutrient additions. To prevent non-nutritive salt buildup, the entire solution was periodically replaced.

D.4 Plant Care During Crisis

The large scale of these NFT experiments where 9 to 28 m^2 of plants were used provided an opportunity to study the pest interactions with the plants. In all cases, control programs were kept to a minimum. Only when the pests appear to threaten large sections of the unit were solutions applied.

Pest control alternatives were always identified with the assistance of expert analysis. Pest control measures applied at infrequent times during the study included resting of the system to enable root drying and regeneration, chemical application, and biological controls.

E. ANALYTICAL APPROACH

E.1. Computerized Summary of Information

All data from pilot scale experiments was entered into disk storage on a Terak computer. Data were stratified by experimental phase, experimental site, the variable tested, the sampling point in the unit where the data was taken, and the sampling date. Data from Cornell pilot units were divided into three groups: (1) data from Phase 0 pilot units, (2) data from 12.2 and 24.4 meter units in Phase 1, and (3) data from the 36.6 meter multi-species units in Phase 1. Hanover data was also divided into three groups: (1) data from the CRREL greenhouse in Phase 0, (2) data from the CRREL greenhouse in Phase 1, and (3) data from the Hanover greenhouse in Phase 1. Bench scale unit data from both Cornell and Hanover units was also entered, each experiment's data grouped separately, but able to be recalled by date. Data from the loading rate simulation (varied flow) experiments at both Cornell and Hanover were evaluated manually. Separate files contained long-term data, such as temperature and incident radiation, which was collected over the duration of the experimental period.

E.2. Long Term Analysis

To facilitate understanding of long term trends, plots of each variable were produced showing the chronological trend over the entire experimental period. These plots included all variables that were routinely determined in the pilot scale units, as well as environmental conditions in the greenhouses.

The arithmetic average for each condition was determined using the following method. The first two measurements were deleted at each condition, and any remaining data points that varied more than twice the standard deviation were deleted.

E.3. Sensitivity of System to Controlling Parameters

Treatment means of each variable were calculated for the pilot scale experiments. These means showed the performance of the variables in each unit or in each part of the units tested under each of the loading rates used. In addition, regression and multiple regression analyses were used to determine correlations between variables or variables and parameters.

E.4. Formulation of Predictive Relationships

Presently there are few methods of predicting the results of exposure of wastewater to a plant system. In an attempt to separate the different mechanisms of control, the above computerized data were examined for empirical relationships between the following variables: grow rate, loading rate, area and weir loadings, temperatures, hydraulic retention time (where available), depth of liquid, mass of plants and/or roots, plant yield, and entrapped microbial mass. The goal of this effort was to be able to predict explicit quality when given certain easily measured or anticipated operating conditions for an NFT unit.

CHAPTER VII

RESULTS

The growth of plants in the nutrient film process as adapted for wastewater treatment was begun in early summer of 1979, and some of the same test units continue in operation some three years later during the preparation of this report. The bulk of the research activity took place in a 24-month period (October 1979 through September 1981)--with a 6-month initial overview referred to as Phase 0, and an 18-month intensive investigation of the parameters that control the process referred to as Phase 1. It should be noted in reviewing the data that the experimental program was designed to develop the feasibility of the nutrient film technique as a total treatment system for gross pollutant removal as well as nutrient control. The sequence of events emphasized treating domestic sewage to a reasonable effluent quality, and subsequent NFT sections were to use this effluent as a nutrient source. Each test condition was considered to be complete when a relatively constant effluent quality was obtained under a given set of conditions. This experimental approach led to rapid development of information on the potential of the system but resulted in conservative estimates of the potential capacity of the system. Under most of the test conditions studied, the plant species were exposed to heavy loadings of sewage after one to six months of growth under non-optimum conditions. This exposure of young plants to pollutants resulted in test units that accumulated root masses from 1 to 5 cm in depth. In contrast, under field conditions after several years of application it would be anticipated that the mature nutrient film would accumulate root systems of 20 to 30 cm deep with dense stands of the plant materials.

The primary test species that was chosen was reed canary grass since it is found throughout most of the United States and is common in wastewater land application treatment systems. It was hoped that this species would grow and survive under heavily loaded conditions in a cold climate with minimum attention for pest control and other special conditions. The results indicate that this was the case and that reed canary grass is a potential candidate for several different applications of wastewater treatment, although it is probably not the optimum species for many applications. An interesting laboratory result illustrates the kind of observations that were experienced in this study. Laboratory technicians conducting the total Kjeldahl nitrogen analysis of the crops were worried about the accuracy of the tests when it was observed that the reed canary grass continuously produced nitrogen contents throughout the year of 5 to 6% of the total dry weight of the grass. The total crude protein content approaching 40% is representative of a valuable animal food and is not known to be the quality of forage produced by field stands of reed canary grass. The fact that the nutrient film application to relatively dilute nutrient solutions was able to do this illustrates one potentially useful by-product of this system.

The following data presentation is an attempt to select typical results from a large amount of data collected from a greater than a 15-person-year effort by a large number of individuals. The detailed data appendices provide comprehensive information on domestic and synthetic sewage pilot scale studies.

A. CHRONOLOGICAL DEVELOPMENT OF TREATMENT CAPACITY OF NFT SYSTEMS

The data were developed using continuously fed units that varied in size from 12.2 to 36.6 meters long (40 to 120 ft), and application rates varied from 0.47 to 11.36 m^3/day (125 to 3000 gal/day). The use of these relatively large systems at high application rates is referred to as pilot applications; since they were conducted in low-cost greenhouses (one of which was built at the Hanover, New Hampshire, treatment plant) the data are a good approximation of what could be obtained at full scale facilities. Examples of the chronological data development illustrating the variability in both the influent and the effluent parameters are discussed in the following paragraphs. Plots of all pilot scale data for all conditions are shown in Appendices B and C for domestic and synthetic wasterwater, respectively.

The treatment efficiency (using synthetic wastewater) by the Cornell NFT units is illustrated in Figures 7.1 and 7.2. Influent COD was targeted to simulate a medium strength sewage at around a 200 mg/ℓ concentration, excepting for the initial runs, which were conducted at around 350 mg/ℓ. The total COD of the effluent remained low throughout most of the testing, even though data from the unit (shown in Figure 1) indicate that the unit was operating under winter light conditions in the Northeast and at an increasing loading rate. Total effluent COD concentrations less than 50 mg/ℓ were typical, excepting for the higher loading conditions (Condition 4 at 40.6 cm/d). Increasing loading rates and the relationship to average radiation are shown in Figure 7.2 of this greenhouse situation.

Similar chronological data development for the application of domestic sewage to the nutrient film is shown in Figure 7.3. The data indicate that although the influent COD ranged from around 250 mg/ℓ up to 350 mg/ℓ the total COD of the effluent was around 100 mg/ℓ. In the mature systems tested at the lower loading rates the effluent COD was often less than 30 mg/ℓ. An example of the comprehensive data collected with the domestic sewage treatment unit is shown in Figure 7.4, in which six major variables are illustrated for the spring of 1981 using the primary settled domestic sewage produced by the Town of Hanover, New Hampshire.

The general trend in wastewater applications illustrates the attempt to achieve high loading rates during the experimental period. Also throughout the period temperature fluctuations occurred in these systems since minimal controls were built into the plastic greenhouses.

The suspended solids removal efficiency is one of the more promising aspects of this system. As can be seen at the top of Figure 7.4, the effluent solids were often less than 10 mg/ℓ and showed only a small effect of increased loading rates. BOD values of less than 20 mg/ℓ were achieved at the lower loading rates but increased to around 50 mg/ℓ at the higher

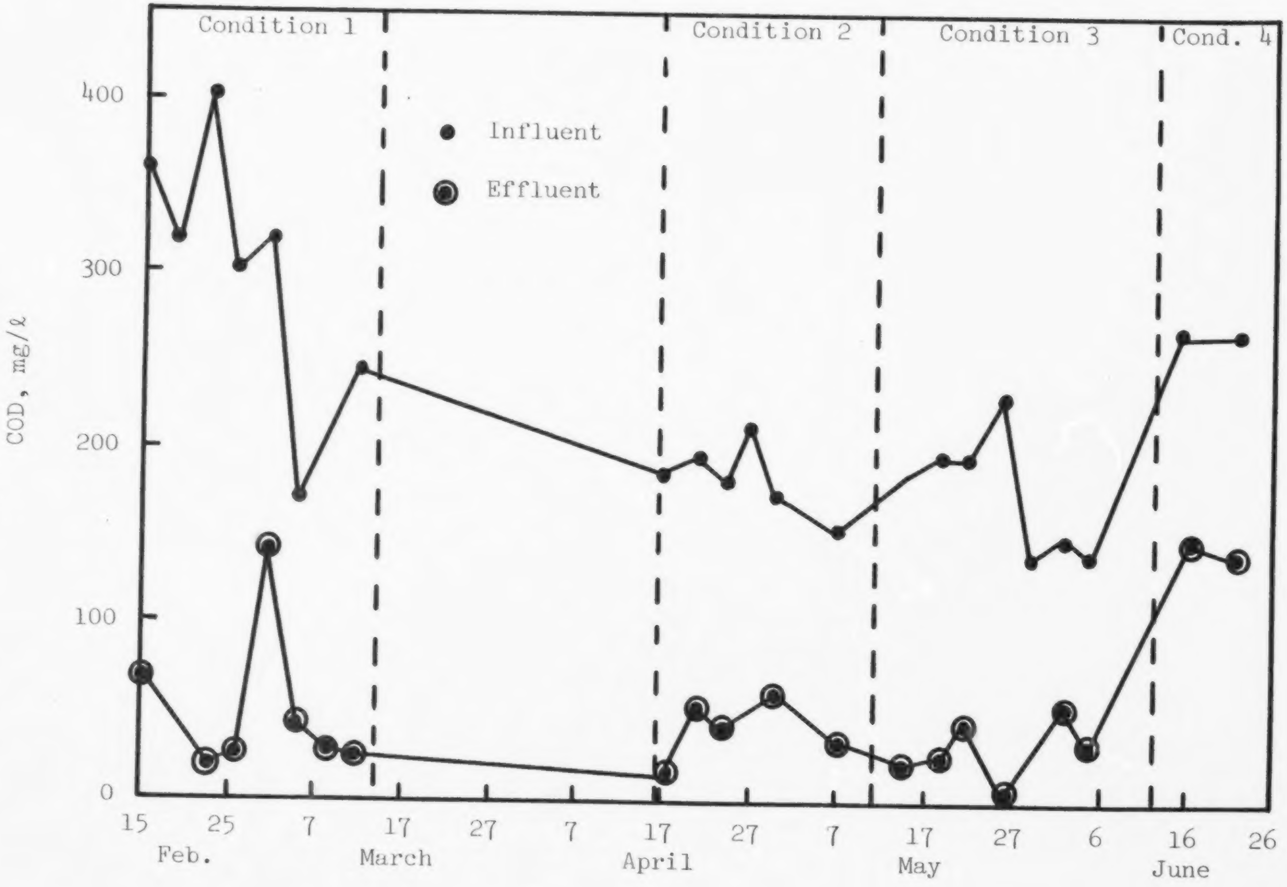


Figure 7.1. Influent and effluent chemical oxygen demand for the Cornell NFT treating synthetic wastewater in spring, 1981. Conditions correspond to areal loadings of 6.9, 10.2, 20.3, and 40.6 centimeters per day, respectively, for a 36 m long unit.

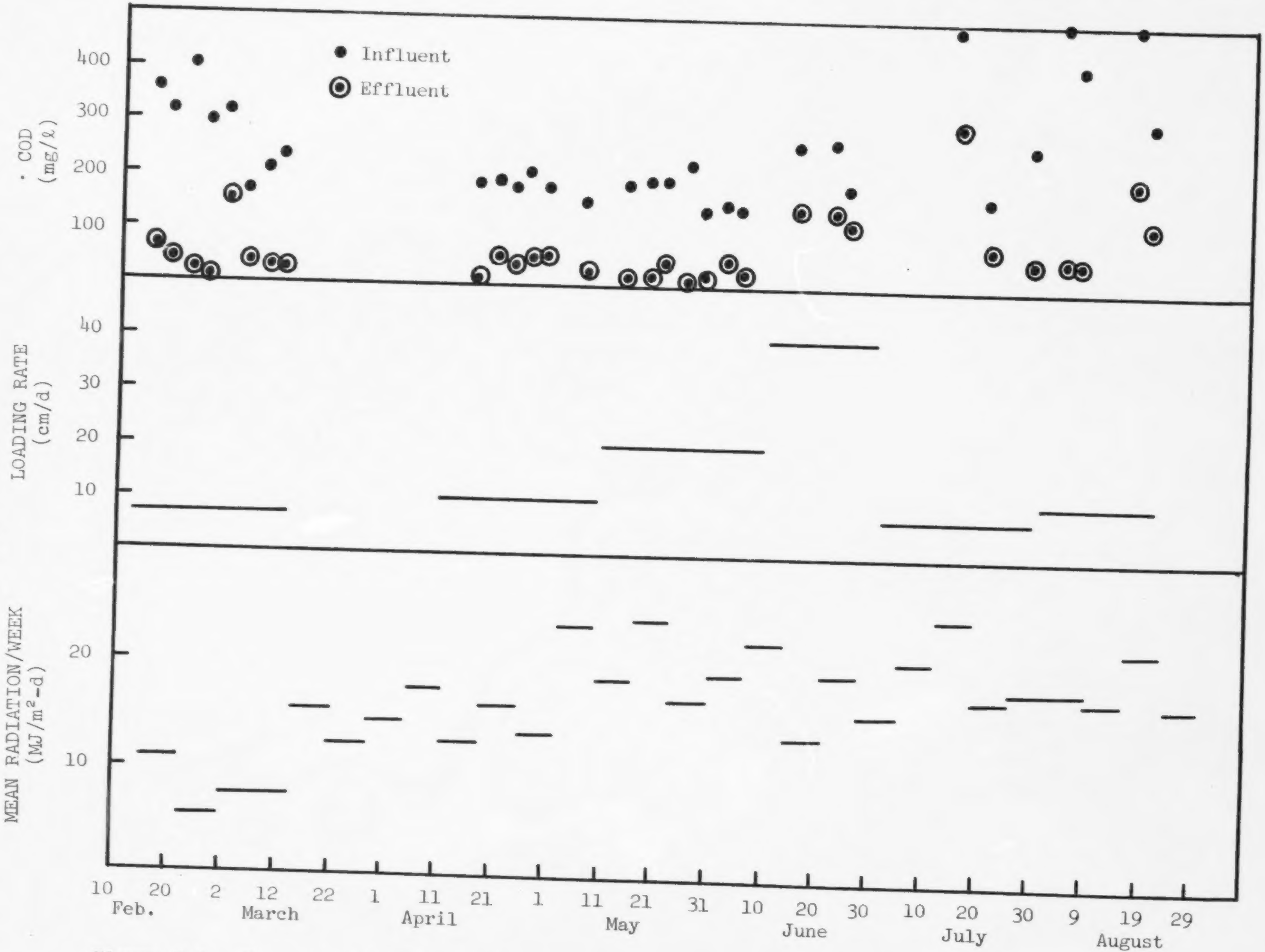


Figure 7.2. Chronological data development for Cornell Phase I (1981) studies with reed canary grass NFT units.

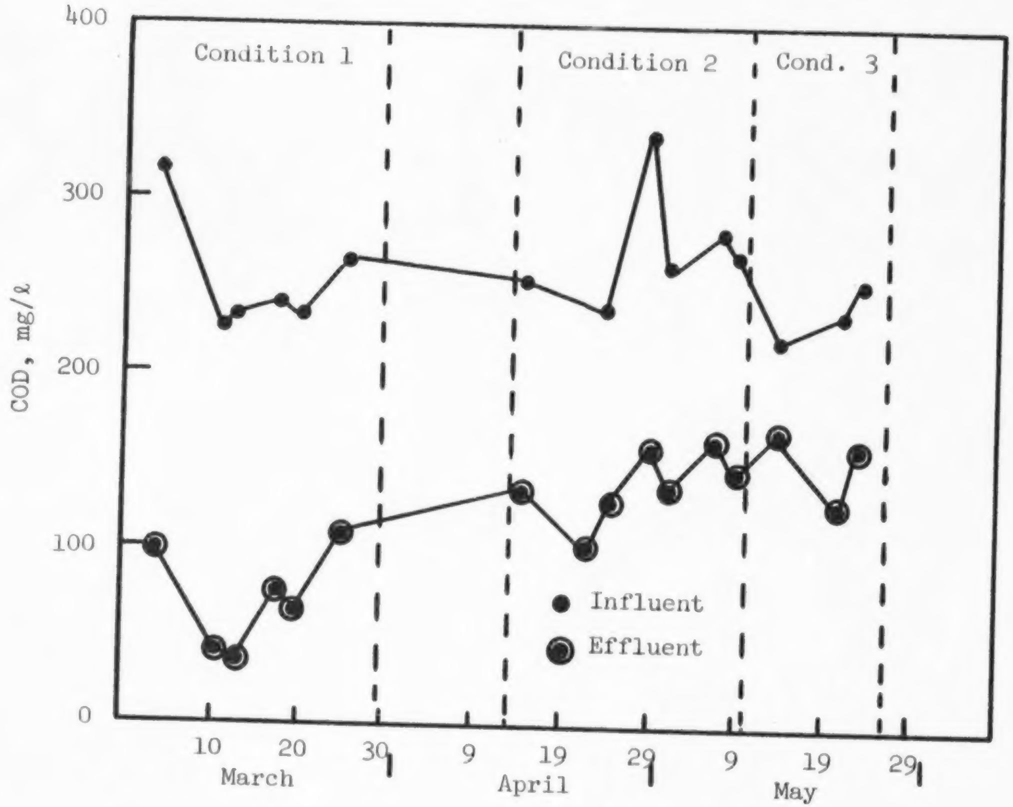


Figure 7.3. Influent and effluent chemical oxygen demand for the Hanover NFT treating domestic wastewater in spring, 1981. Conditions correspond to areal loadings of 6.9, 10.2 and 20.3 cm per day, respectively, for a 36 m long unit.

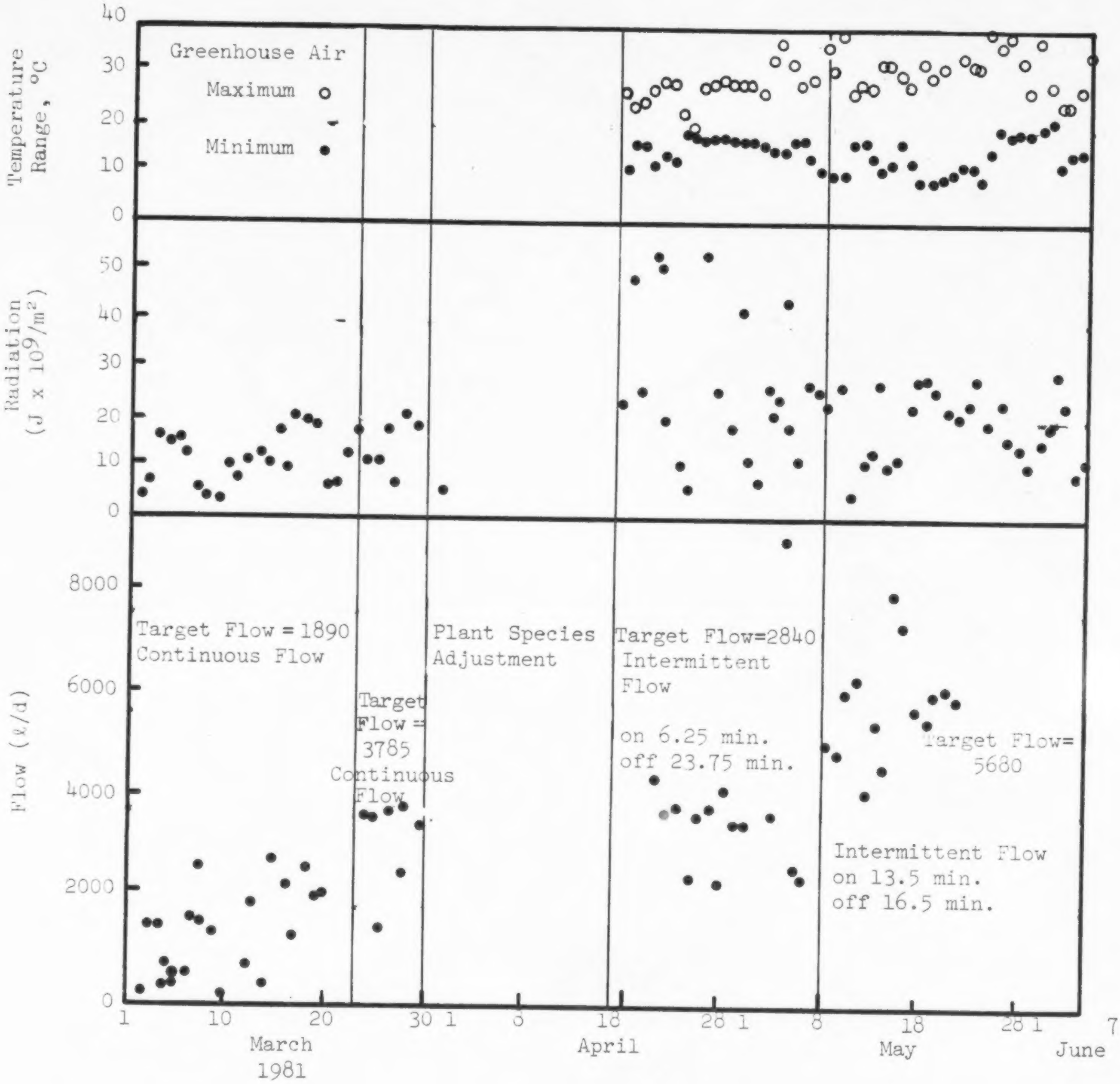


Figure 7.4a. Example of chronological data development for domestic sewage testing with the NFT at Hanover, New Hampshire.

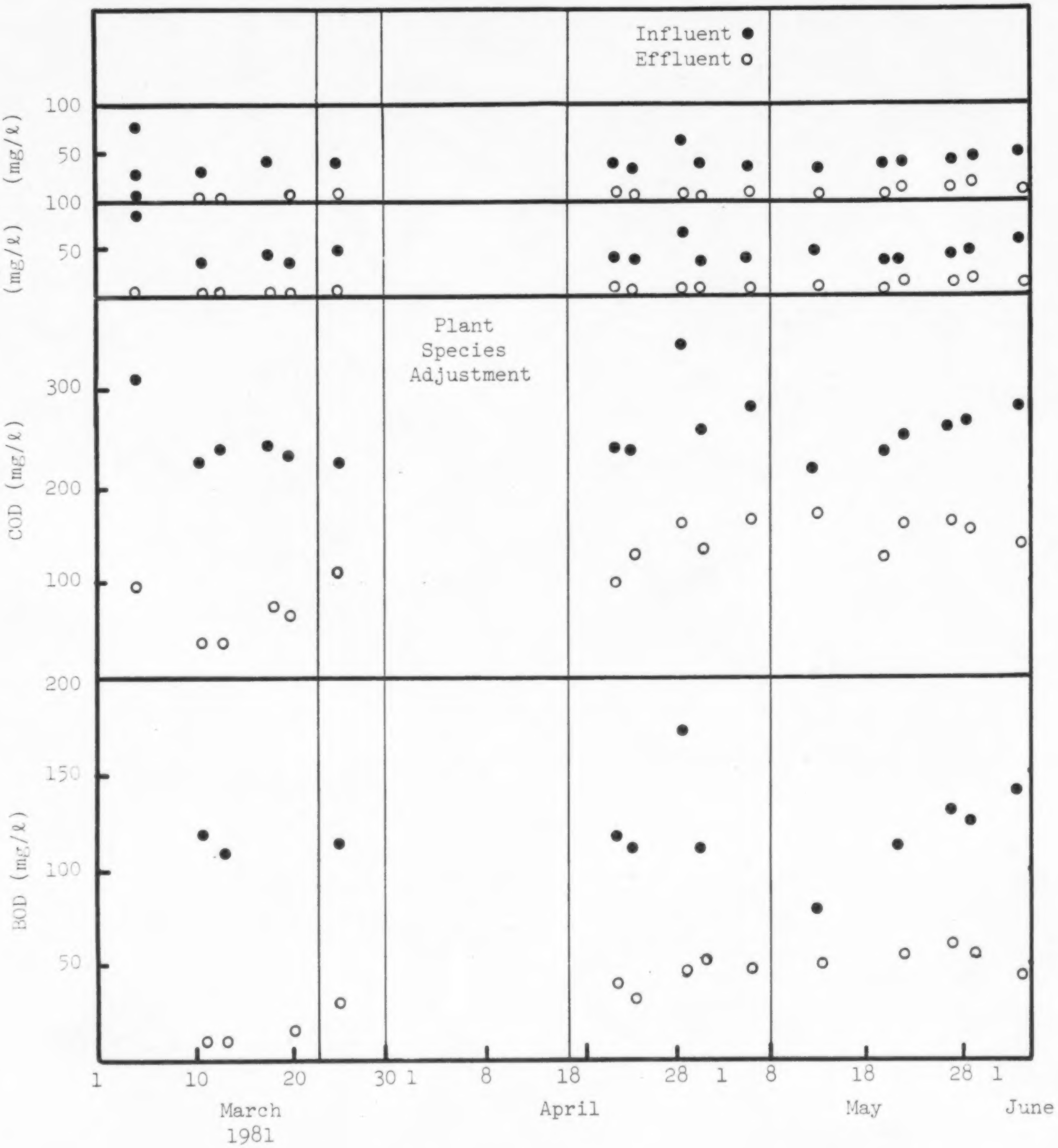


Figure 7.4b. Example of chronological data development for domestic sewage testing with the NFT at Hanover, New Hampshire.

loading rates. Subsequent data presentation will examine the relationship between loading and hydraulic retention time and effluent quality. It is important to note that the influent sewage temperature in these systems during the winter often was 7° to 8°C, thus causing problems in achieving efficient pollutant removal.

The large number of uncontrolled variables caused analysis of the results of this study to be a difficult problem. The process efficiencies must be a function of temperature, light period and radiation intensity. However, the effect of light period and radiation intensity did not appear to be a major variable for BOD and suspended solids removal when the plants were in a healthy condition. This most likely is related to the fact that the removal of these constituents is a biological/physical/chemical phenomenon not related to plant uptake. Of course, it was anticipated that nutrient uptake would probably be a function of the plant productivity and microbial activity in the root zone. Figure 7.5 is a data summary of the productivity of reed canary grass grown for long periods of time under limited light and nutrient conditions.

B. CHARACTERISTICS OF THE NFT IN TREATING SYNTHETIC WASTEWATER AND DOMESTIC SEWAGE

Long-term operation of pilot scale NFT models with synthetic wastewater and actual domestic sewage enabled the parametric evaluation of the process. Tables 6.12 and 6.13 present a summary of the steady state conditions for these continuously fed pilot units operating on synthetic and domestic wastewater, respectively. Between November of 1979 and August of 1981 a total of 16 steady state conditions were observed with synthetic wastewater and 13 conditions were examined with domestic sewage in Hanover. Twenty-two pollutant variables were examined in the synthetic wastewater, and seventeen variables were tested in the domestic sewage units. Each steady state condition is an average of a number of analyses, between four to fifty-five, depending on the analysis. Results with each of the major variables will be discussed briefly in the following section. Examination of the relationships of loading rates and mechanisms responsible for the following observations will be discussed in subsequent sections.

The variables that are compared in this study are listed in Table 7.1.

B.1. pH

The wastewater in both the synthetic and domestic studies varied only several tenths of a pH unit and remained slightly on the alkaline side of neutral. Synthetic wastewater was usually introduced around a pH of 7.0 and through the first unit varied approximately 0.2 to 0.3 of a pH unit in the first unit. A variation of approximately one pH unit occurred in the 36.6 meter unit with an effluent of 7.7 to 8.0. The domestic sewage unit varied less, with an influent pH of around 7.3 and an effluent slightly lower than the influent values, with a value of 6.9 to 7.0 quite common. The limited variation in both synthetic and sewage units suggests that microalgae growth was not a significant factor affecting pH in the mature steady conditions.

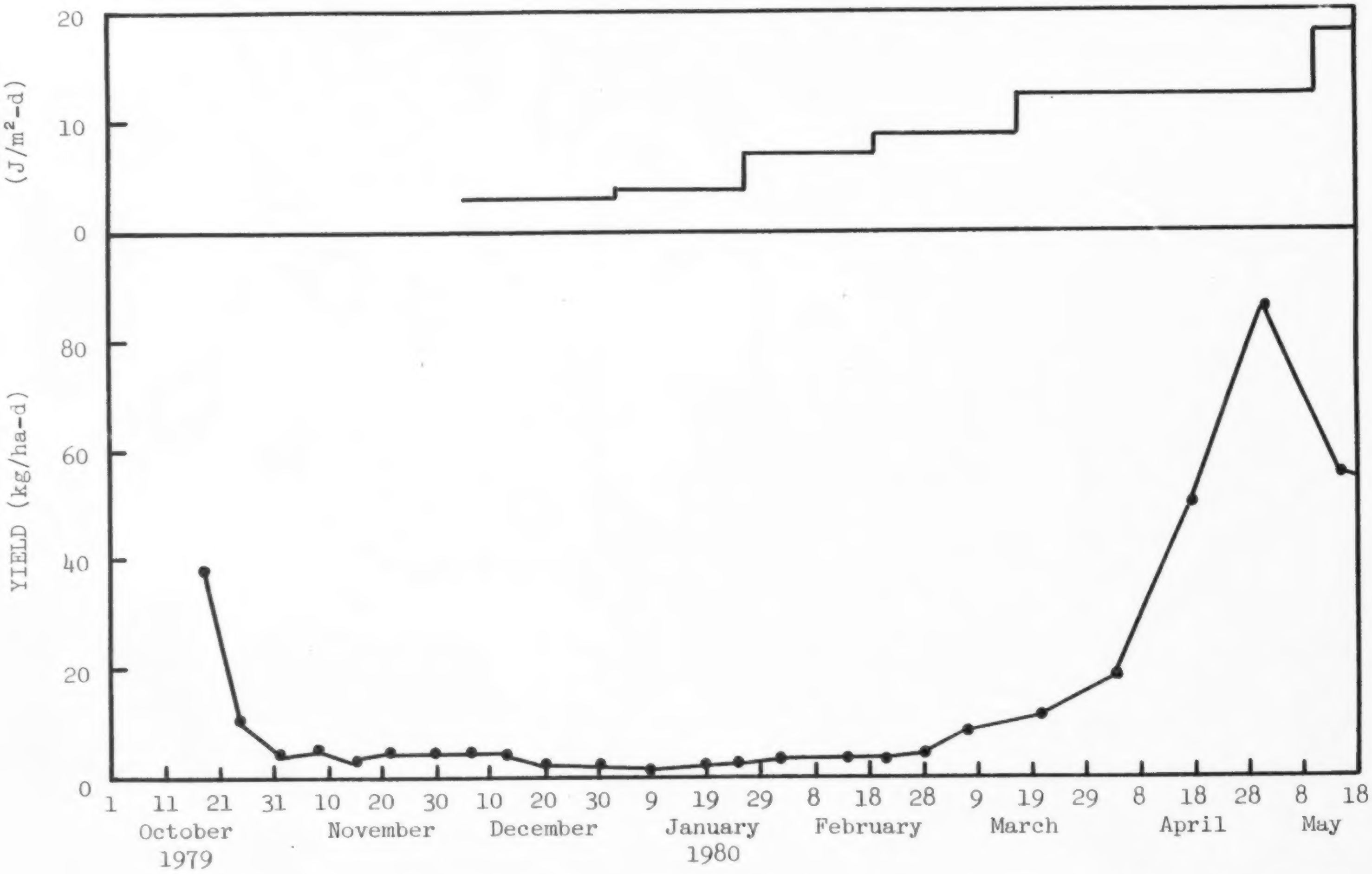


Figure 7.5a. Incident radiation and yield of reed canary grass grown in continuing NFT culture in the Cornell Bracehouse over the course of experimentation. The unit was used as a synthetic sewage test unit from October 1979 to November 1980, after which it was used as a biomass and evapctranspiration control unit for larger systems.

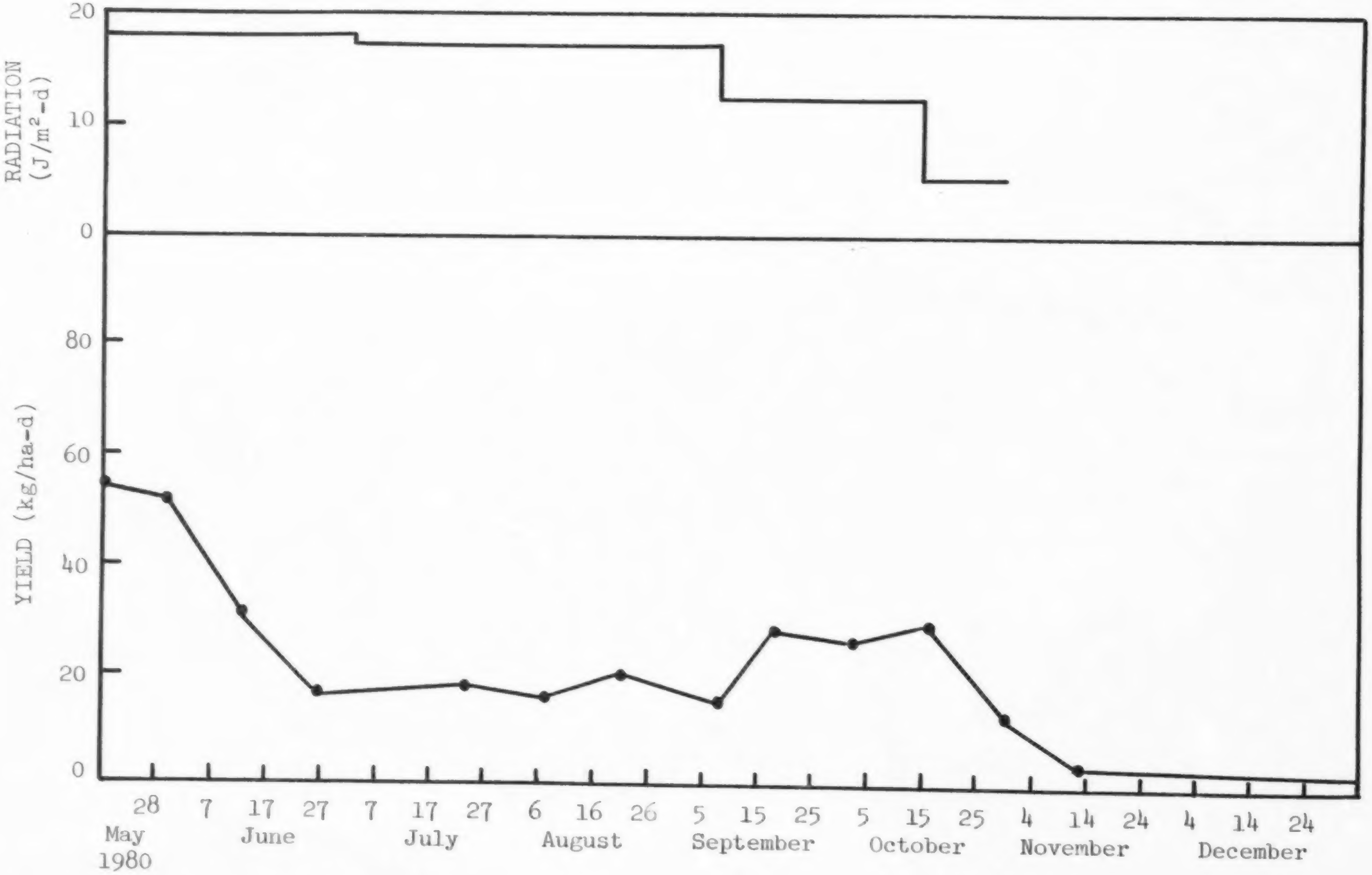


Figure 7.5b. Incident radiation and yield of reed canary grass grown in continuing NFT culture in the Cornell Bracehouse over the course of experimentation. The unit was used as a synthetic sewage test unit from October 1979 to November 1980, after which it was used as a biomass and evapotranspiration control unit for larger systems.

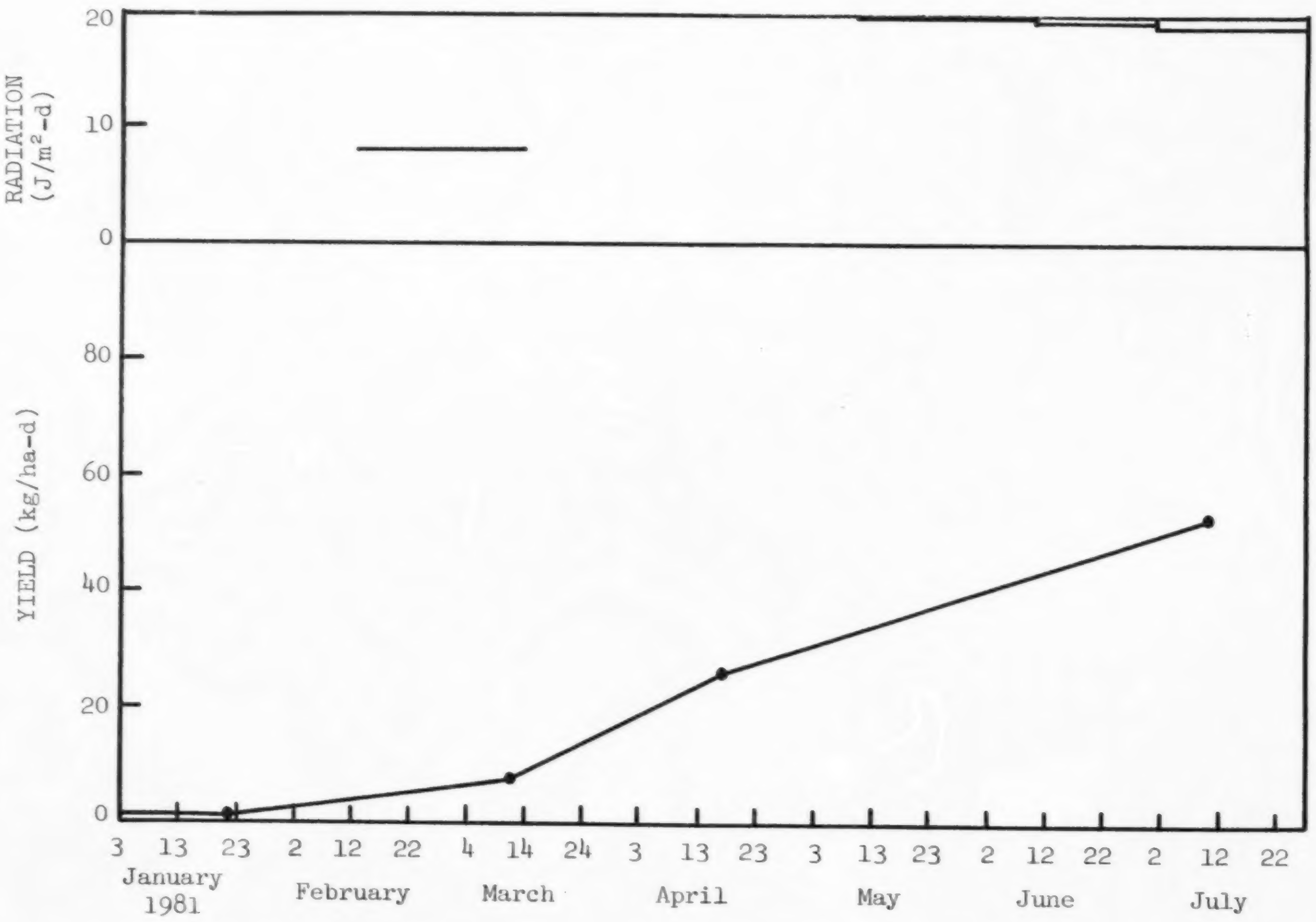


Figure 7.5c. Incident radiation and yield of reed canary grass grown in continuing NFT culture in the Cornell Bracehouse over the course of experimentation. The unit was used as a synthetic sewage test unit from October 1979 to November 1980, after which it was used as a biomass and evapotranspiration control unit for larger systems.

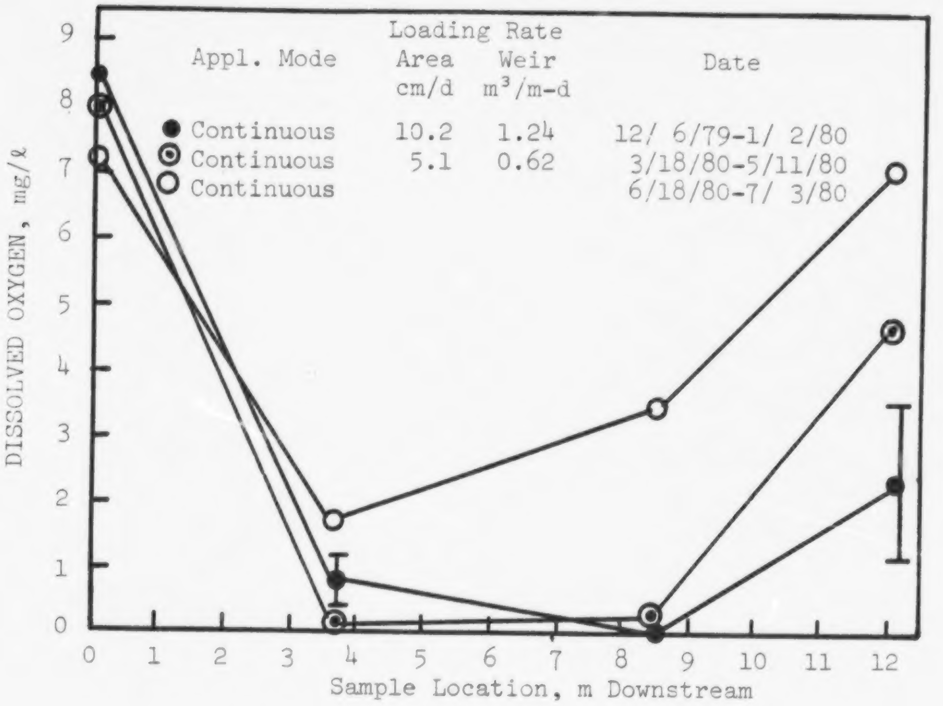
Table 7.1. VARIABLES MEASURED IN TESTING PILOT SCALE NFT SYSTEMS WITH SYNTHETIC AND DOMESTIC SEWAGE.

Synthetic Sewage Variables	Domestic Sewage Variables
Flow	Flow
pH	pH
Dissolved Oxygen	Dissolved Oxygen
Air Temperature	Air Temperature
Chemical Oxygen Demand	Chemical Oxygen Demand
Soluble Chemical Oxygen Demand	Soluble Chemical Oxygen Demand
Ammonia Nitrogen	Ammonia Nitrogen
Soluble Ammonia Nitrogen	Nitrate Nitrogen
Nitrate Nitrogen	Total Nitrogen
Soluble Nitrate Nitrogen	Total Phosphorus
Organic Nitrogen	Soluble Phosphorus
Soluble Organic Nitrogen	Suspended Solids
Total Phosphorus	Volatile Suspended Solids
Soluble Phosphorus	Solar Radiation
Total Solids	Biochemical Oxygen Demand
Total Volatile Solids	Total Organic Carbon
Total Suspended Solids	Sewage Temperature
Volatile Suspended Solids	
Zinc	
Cadmium	
Solar Radiation	
Relative Humidity	

The microalgae was a problem in the early stages of operation and testing (before plants developed a dense canopy), but it was not a variable in the steady state values.

B.2. Dissolved Oxygen

The dissolved oxygen around the roots in an NFT system is a critical parameter for plant production and pollutant removal. Typical dissolved oxygen profiles in the unit are presented in Figures 7.6 and 7.7. Figure 7.6 compares the effect of loading rate and continuous application to the intermittent applications during much of the synthetic sewage study. This information indicates that intermittent application provides some control over the dissolved oxygen in the wastewater. Figure 7.7 compares the dissolved oxygen in the continuously operated synthetic wastewater unit with domestic sewage applied intermittently. Although intermittent application enabled the dissolved oxygen concentrations to be maintained at an average value of 2 to 3 mg/ℓ at loading rates of 10 cm/day, it is clear that dissolved oxygen at high loading could be a problem. Low dissolved oxygen at high loading rates is likely. These values will be useful in interpreting the subsequent lack of nitrification that is presented in the nitrogen removal information.



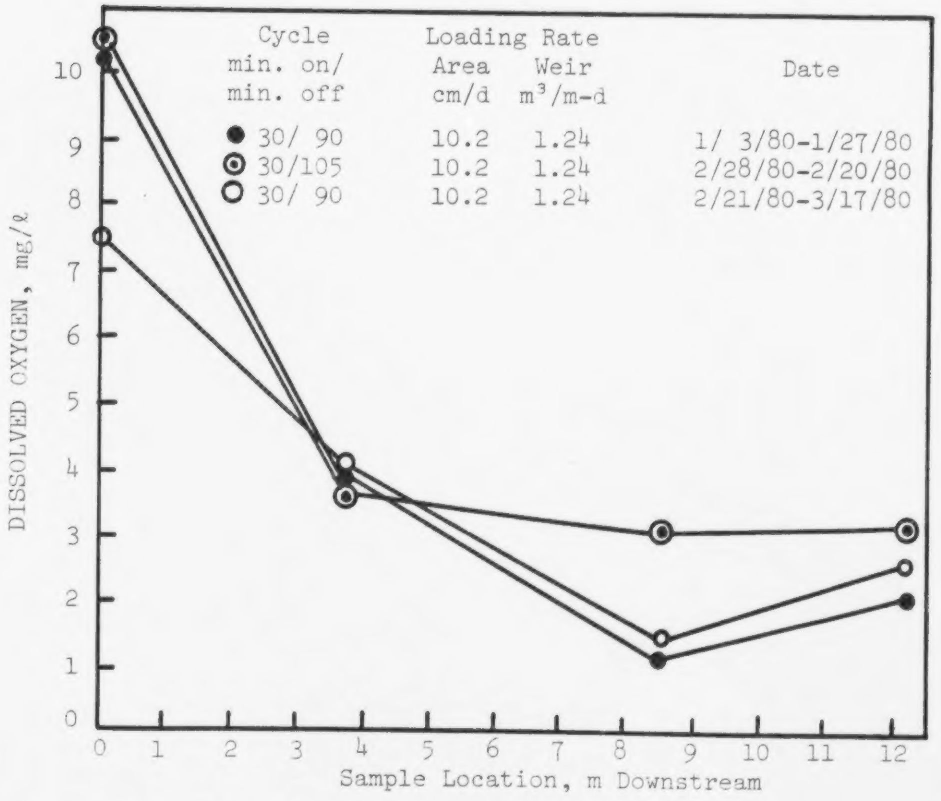


Figure 7.6. Dissolved oxygen concentration in reed canary grass NFT treating synthetic wastewater.

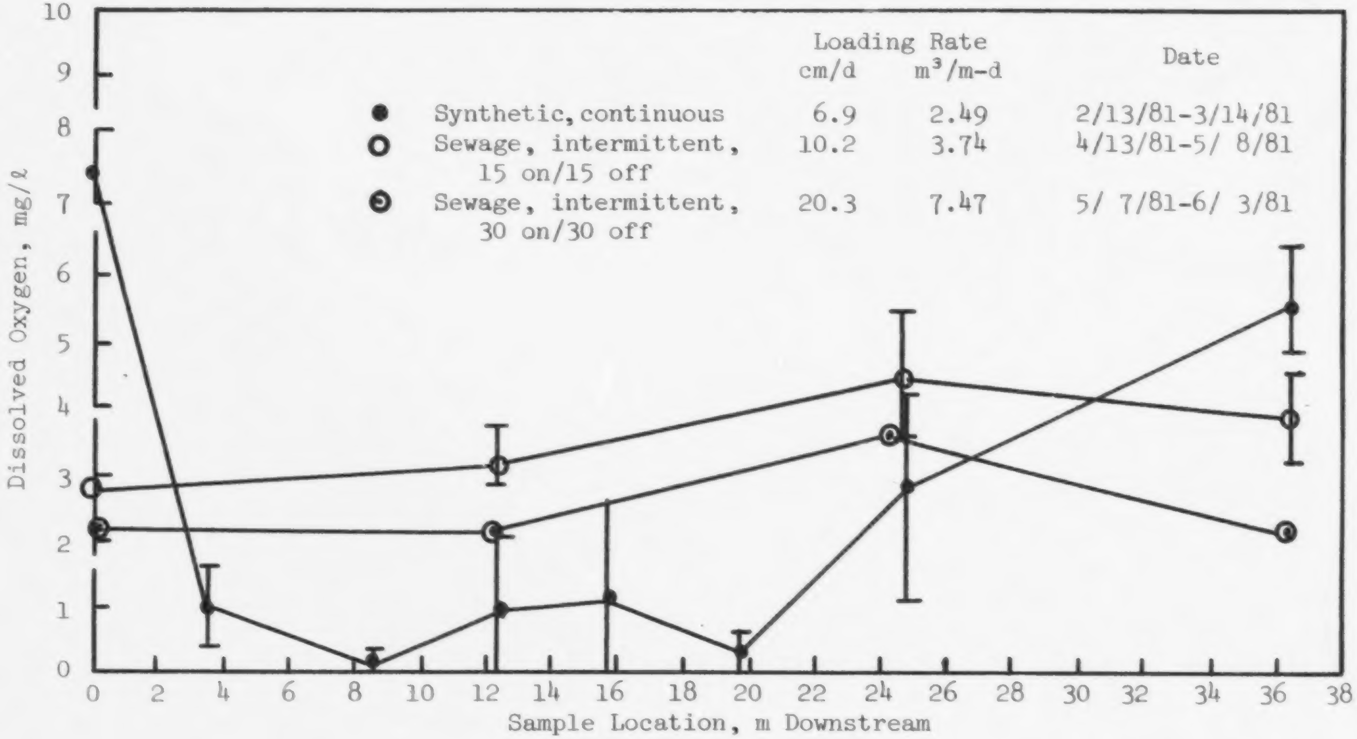


Figure 7.7. Dissolved oxygen concentration in multispecies NFT unit treating primary settled domestic sewage at Hanover, New Hampshire.

B.3. Temperature

No attempt was made to control the wastewater temperature in any system, so the influent temperatures in the wintertime varied with the domestic sewage-studies. The low temperature in January averaged 7.6°C with a standard deviation of 2.4°. The effluent during this month was 12.8°C, with a standard deviation of 0.5°. At other times of the year, common values of sewage in New Hampshire was 9 or 10°C. This temperature would increase by an average of 3° or 4°C going through a 12-meter long unit. Increases in sewage temperature during the summertime ranged from 14°C to as high as 24.8°C, with a standard deviation of 6°C. A potential increase in temperature as sewage moves through the system needs to be taken into account in evaluating the applications of the technology.

While few synthetic sewage temperature measurements were made, some generalities can be made. In the Cornell Bracehouse air temperature is quite sensitive to solar radiation; and since a large volume of synthetic sewage was prepared in the greenhouse, the influent temperature of this sewage approached the average air temperature in the greenhouse. This influent temperature ranged from about 12°C in winter to about 17°C in summer. Similar small rises in temperature were measured in synthetic sewage as it passed through the units, although only a small number of these measurements were made.

B.4. Suspended Solids

The suspended solids data generated from the synthetic wastewater system are of limited value since the influent feed had few solids. The suspended solids reported in Table C.21 in the appendix for synthetic wastewater represents microbial growth in the feed at the room temperature. This varied from 2 to 8 mg/ℓ. However, the concentration of effluent suspended solids from the unit is a function of the large accumulation of microbial solids in the root system that are continuously lost as the microbes grow and slough from the root mass. At a loading rate of 10 cm/day, the typical effluent solids from the synthetic wastewater was approximately 7 mg/ℓ. Suspended solids concentrations in the effluent from the synthetic studies seldom exceeded 20 mg/ℓ.

The effluent suspended solids with the sewage studies represent some of the more important information from this study. Influent total suspended solids concentration varied widely from a dilute 35 mg/ℓ in the wintertime to a high of 140 mg/ℓ. Effluent solids were usually less than 30 mg/ℓ and in the 36-meter long unit varied between 4 and 16 mg/ℓ up to a loading rate of 20 cm/day which was the highest loading tested. A typical effluent solids profile through the NFT unit with reed canary grass and in a multiple species unit is shown in Figure 7.8. An analysis of the influence of various parameters on effluent solids concentration will be given in a subsequent section.

An important observation related to suspended solids was the nature of the suspended solids within the system. It had been envisioned that much of the solids would become entrapped in the root mass and that this material would

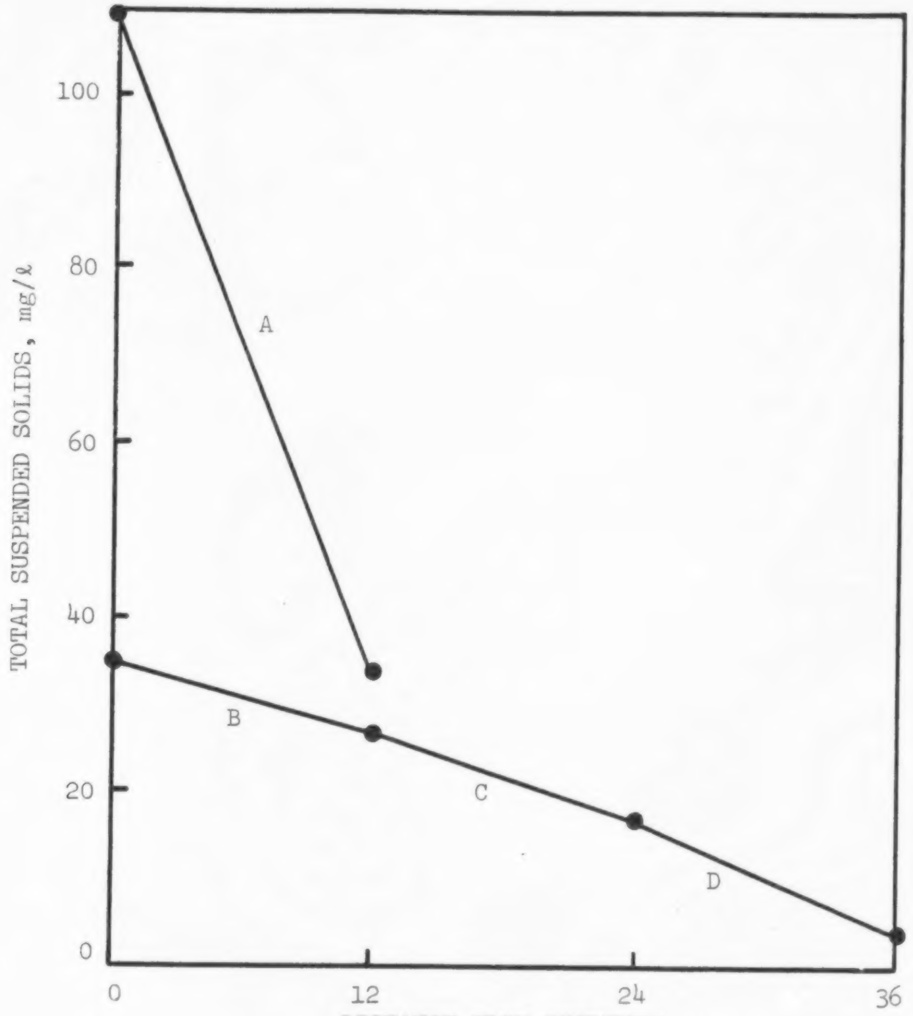


Figure 7.8. Mean suspended solids concentrations in NFT systems treating domestic wastewater at 10.2 cm/d. Curve A shows a 12 m canary grass system with a relatively high SS influent. Curve B-C-D shows a three-part NFT system consisting of phragmites, cucumbers, and canary grass (in order from influent).

remain in the unit. Observations of the Hanover domestic sewage indicated that the suspended solids were rapidly flocculated into relatively large clumps of material. These materials settled rapidly but also moved around within the system on an intermittent basis. This observation leads to the possibility of flushing the system with rapid additions of the wastewater.

B.5. Turbidity

As indicated in the suspended solids removal section, the NFT produced a relatively clear effluent. Turbidity measurements with the NFT system treating domestic sewage indicated a reduction in a 12-meter length from around 50 JTU to less than 20 in almost all cases. At a loading rate of 20 cm/day during June on reed canary grass a typical decrease from 29 to 6 JTU was recorded.

B.6. Chemical Oxygen Demand

A comparison of changes in total and soluble COD for the synthetic wastewater is shown in Figure 7.9. In most cases the COD was rapidly removed, and at 5 cm/day decreased from 250 mg/ℓ to 60 mg/ℓ in a 12-meter section. Since the influent organics were mainly soluble, the total COD closely followed the soluble COD in the synthetic wastewater. Figure 7.10 compares the influence of temperature and maturity on similar systems at the higher loading rate of 10 cm/day. As the system became more mature, it was clear that loadings of 20 cm with a 12-meter system were effective in removing COD down to low levels. The influence of the length of the system on soluble COD is shown in Figure 7.11 where two single species units of different lengths were compared with a multiple species units of a longer length. These data clearly indicate that the process is highly efficient in removing organics and that there appears to be a relationship between loading rates and the length of the unit. This will be examined in subsequent sections.

A comparison of the total COD removal profile to soluble COD with domestic sewage is shown in Figure 7.12. Because of the influence of suspended solids there is a larger difference between these two parameters than was present in synthetic sewage. Total COD removal appears to be similar to synthetic wastewater. A larger fraction of soluble COD appears to be nonbiodegradable in domestic sewage. This is indicated by lower percentage reductions of soluble COD in domestic sewage; also all COD in synthetic sewage originated as sucrose.

Organic removals are examined in Figure 7.13 by comparing the total BOD to the soluble BOD in domestic sewage. At a loading rate of around 7 cm/day the effluent from the second section approached 30 mg/ℓ of BOD, and the effluent from the third section averaged 10 mg/ℓ in most runs. Doubling that application rate increased the effluent concentration from the second unit to 50 mg/ℓ BOD and 33 mg/ℓ from the third unit. At a 20 cm/day loading rate this increased to an average of 41 mg/ℓ from the effluent from the third unit.

A comparison of the winter operation to the summer operation with respect to the total COD removal efficiencies is shown in Figure 7.14. In addition to

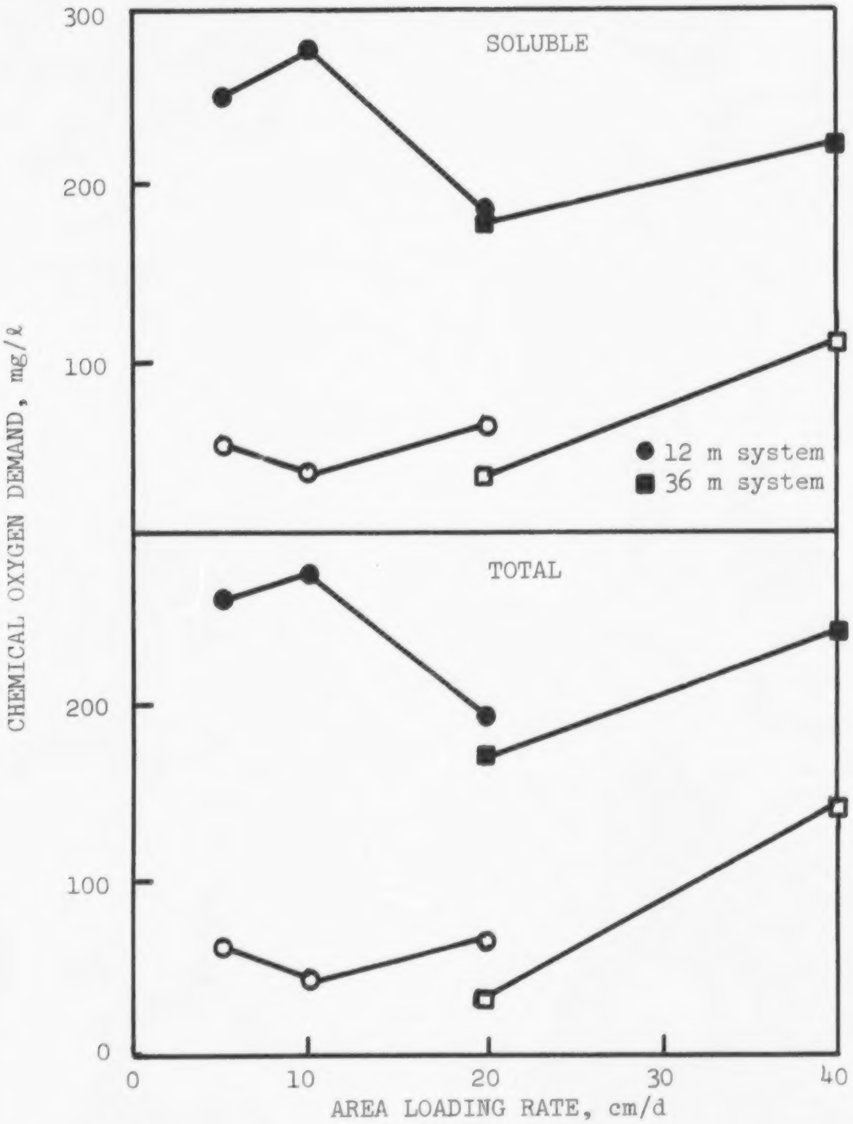


Figure 7.9. Reductions of total and soluble chemical oxygen demand concentrations in synthetic wastewater through 12 m and 36 m systems. Note similarity between total and soluble COD for both influent (solid symbols) and effluent (open symbols) synthetic wastewater.

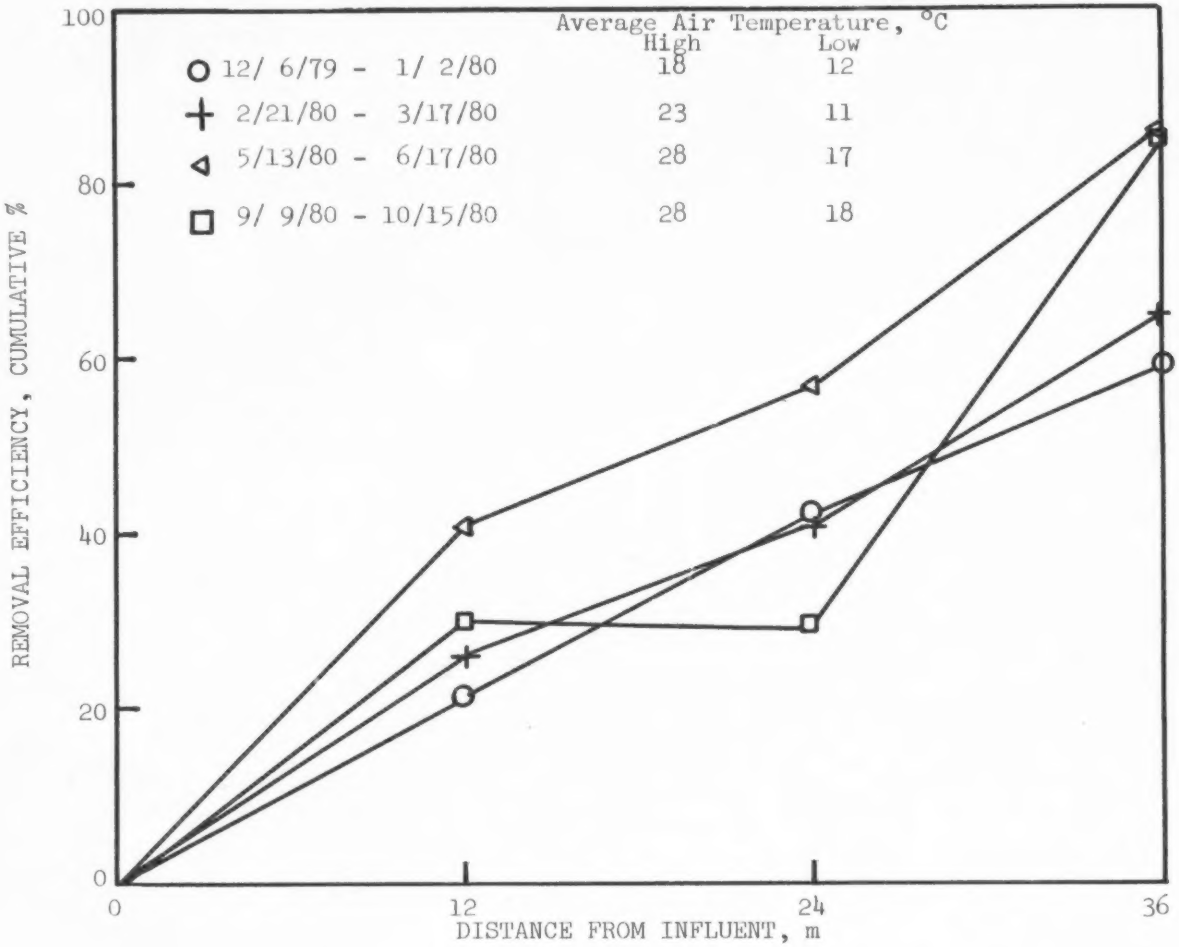


Figure 7.10. Chemical oxygen demand removal efficiency at different stages of stand maturity and under different mean temperatures. All systems used canary grass and synthetic sewage at a loading of 10.2 cm/d.

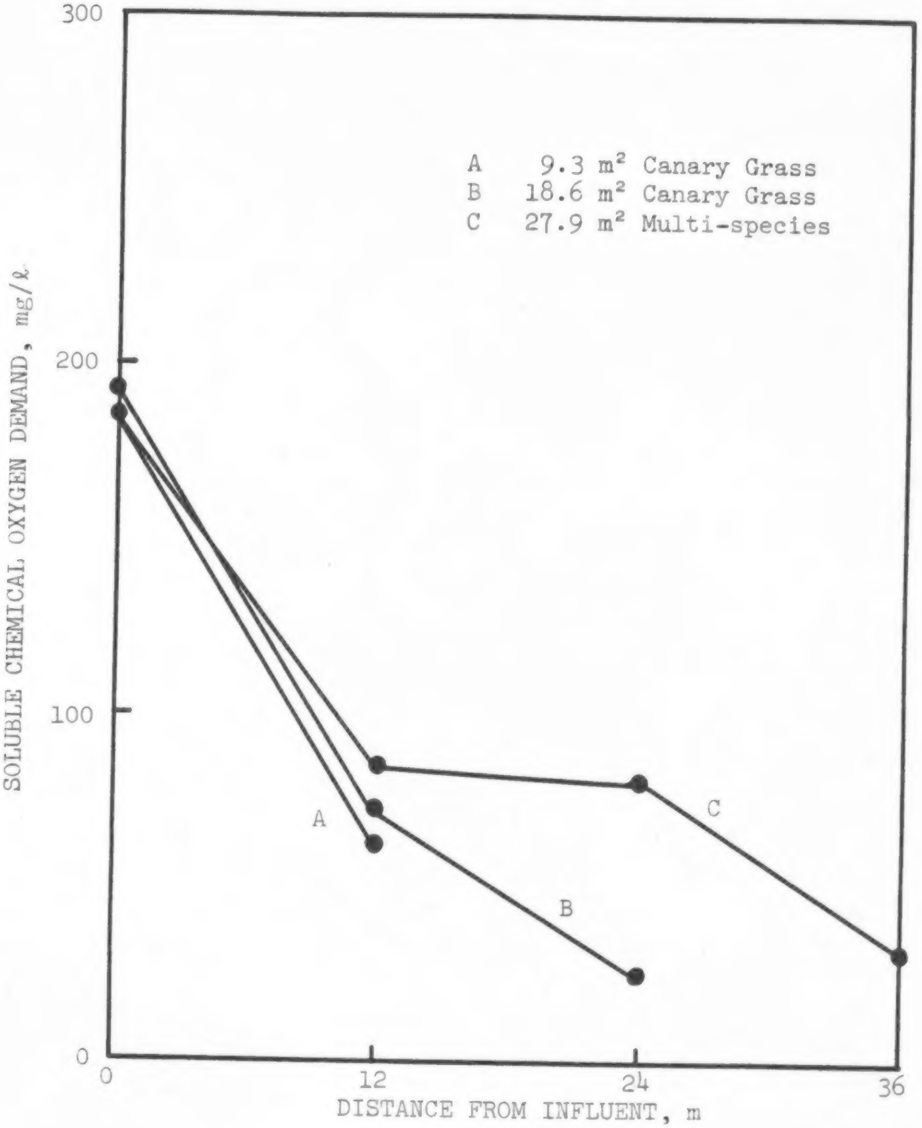


Figure 7.11. Influence of system length on soluble COD removal from synthetic sewage at an area loading rate of 20.3 cm/d. Systems A and B contain reed canary grass only, while System C consists of cattails and bulrushes, phragmites, and canary grass (in order from influent).

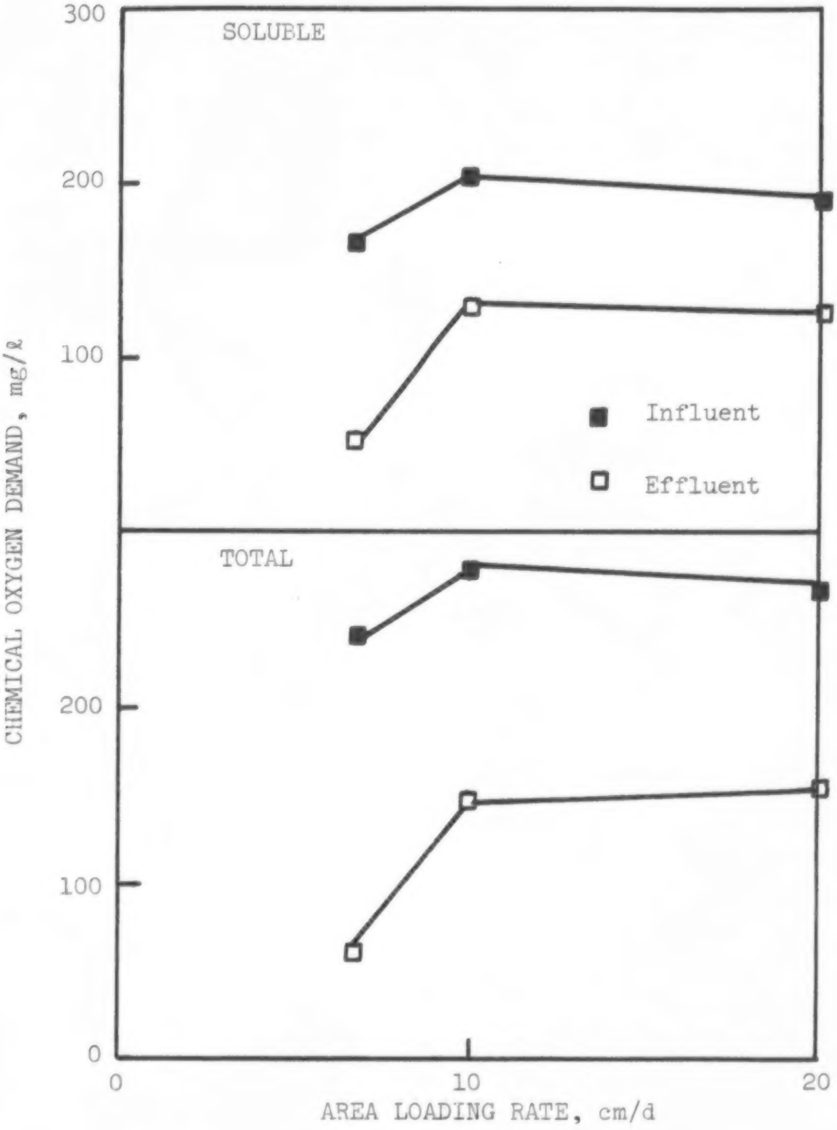


Figure 7.12. Reductions of total and soluble chemical oxygen demand concentrations in domestic sewage in 36 m multiple species NFT units, which were tested at three different loading rates.

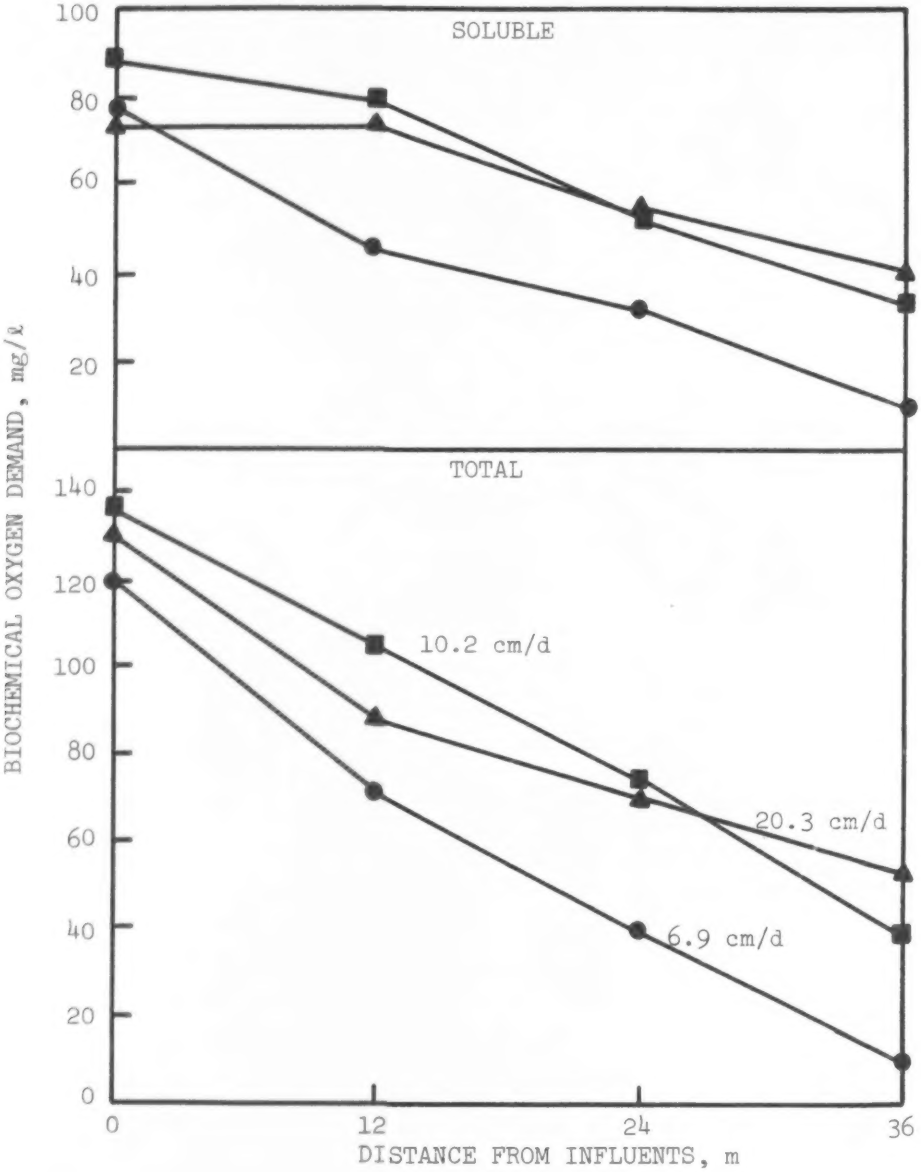


Figure 7.13. Total and soluble oxygen demand concentrations at various biochemical points in 36 m multiple species unit treating domestic wastewater. Three loading rates are shown.

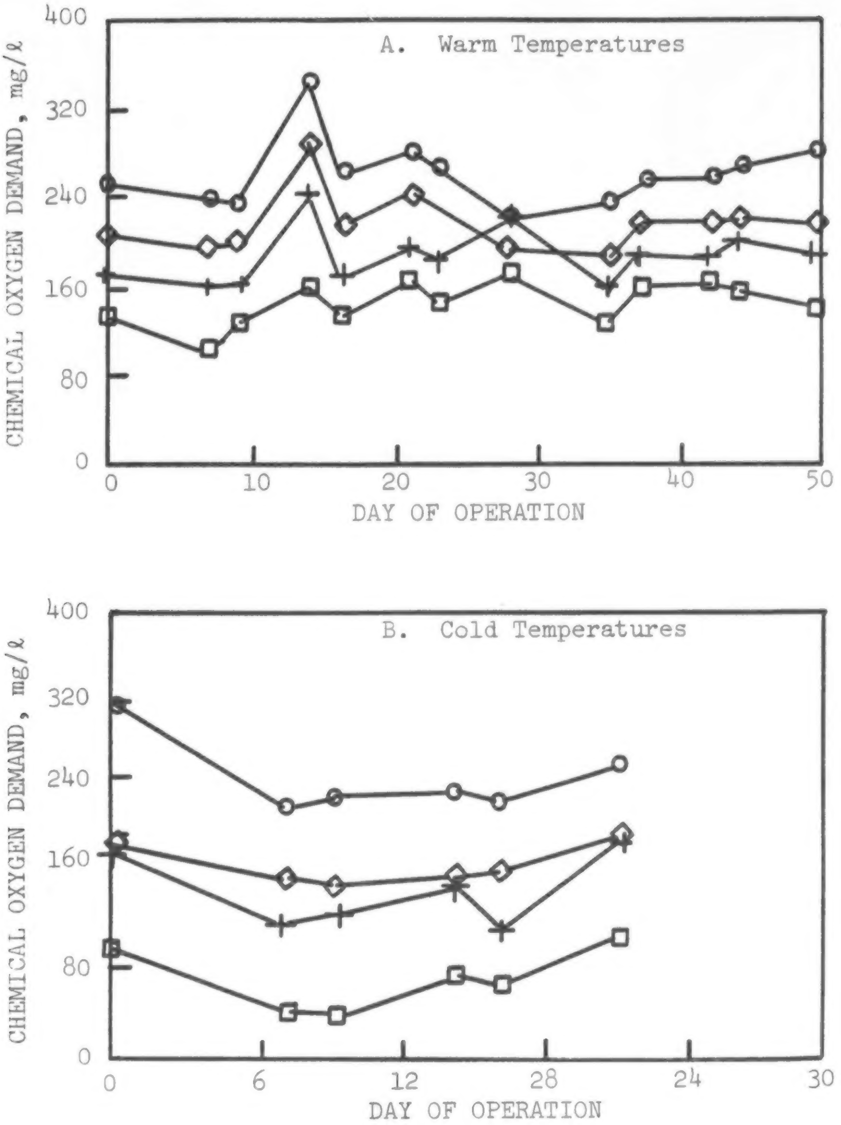


Figure 7.14. Comparison of COD removal from domestic sewage during relatively warm (A) and cold (B) temperatures.

○ = Influent
◇ = Effluent from first unit
+ = Effluent from second unit
□ = Effluent from third unit

the effect of temperature this figure shows a significant influence on BOD removal with length. This is most likely related to the hydraulic retention time in the channel.

B.7. Nitrogen

In general, the nutrient removal for continuous flowing units was low. This was primarily related to the fact that most of the tests conducted were at high loadings to achieve high BOD and suspended solids removal rates. Therefore, the nutrient loadings on these plant systems at high organic loading rates should not be expected to result in efficient nutrient management. Example reduction of total nitrogen with the synthetic wastewater shows effects of the length of the units in Figure 7.15. Maximum reduction of nitrogen in these units occurred at the lower loading rates of 5 cm/day and achieved a maximum of 12 to 15 mg/ℓ of nitrogen removed from the system. Figure 7.16 compares total Kjeldahl nitrogen removal at varying loading rates. The relationship of plant yield and other nitrogen removal processes will be discussed later.

Since the influent synthetic sewage contained urea nitrogen, hydrolysis of urea to ammonia occurs rapidly in the synthetic wastewater. The ammonia concentration in the sewage represented a major change in nitrogen species as shown in Figure 7.17. Approximately 10 mg/ℓ of ammonia nitrogen was removed in these systems at the lower loadings, and at high loading rates the removals were less.

The intent of testing the nitrogen cycle was to define conditions under which nitrification could be achieved so that a denitrification system could be added as one means of removing nitrogen from the system. However, throughout the study there was nearly a complete absence of nitrification. Although numerous analyses were done for nitrate nitrogen for both synthetic wastewater and the domestic sewage, the highest concentration of nitrate observed in the effluent was 4 mg/ℓ in one early spring operation at a low loading rate of 5 cm/day. At higher loading rates almost no nitrates were observed. Although this was a surprising observation, it is most likely related to low hydraulic retention times that were observed under most testing conditions and the higher organic loading rates that were used to define the kinetics of the organic solids removal. All of the loading rates tested resulted in low dissolved oxygen values that could inhibit nitrification. Additional analysis of this lack of nitrification in the systems will be reviewed under the root analysis section.

B.8. Phosphorus

The phosphorus removals were similar to the nitrogen removals in that the total efficiencies were relatively low. A comparison of the total phosphorus removed from the synthetic wastewater at the 5 and 10 cm/day loading rates is shown in Figure 7.18. Maximum removal efficiency occurred in the early summer with the 5 cm/day loading rate, resulting in about a 50% removal of total phosphorus. A similar comparison is given in Figure 7.19 for total phosphorus concentration changes in the NFT units treating domestic sewage. Total reductions of 2 or 3 mg/ℓ (amounting to about 30 percent

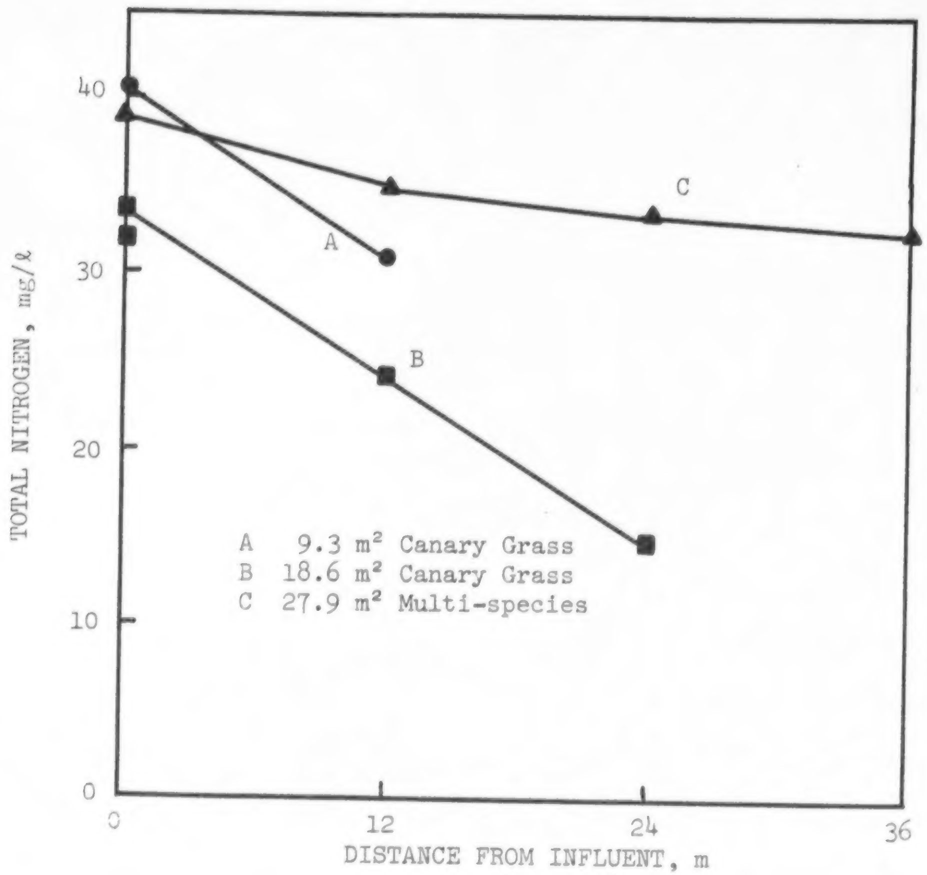


Figure 7.15. Total nitrogen concentration of synthetic wastewater in three different NFT systems at an area loading rate of 10 cm/d.

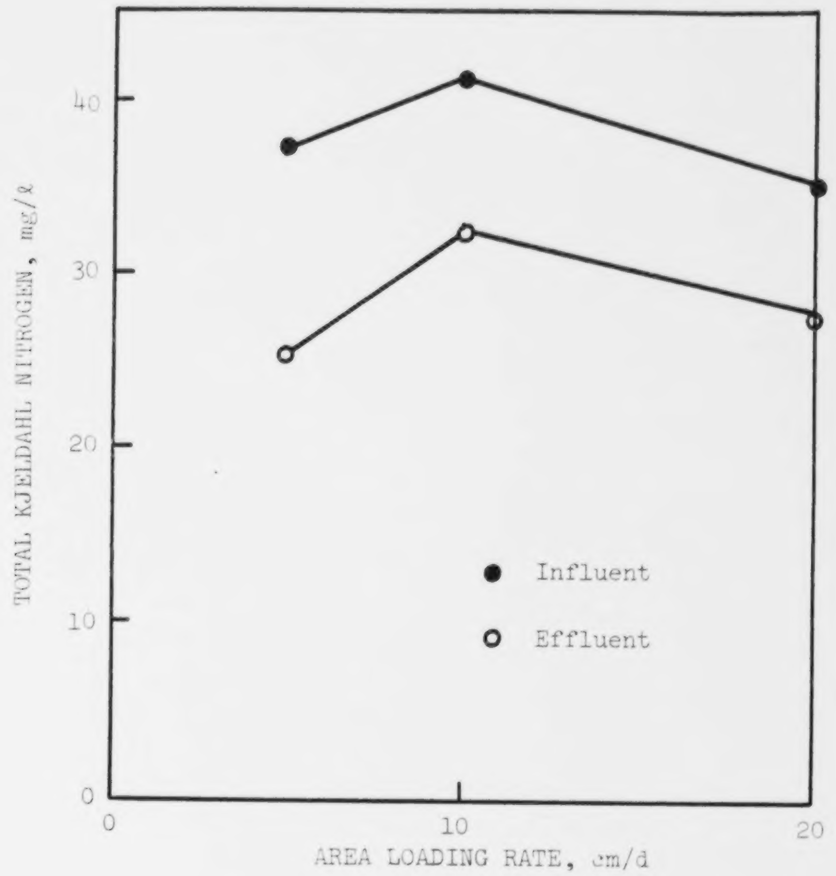


Figure 7.16. Total Kjeldahl nitrogen concentration reductions in 9.3 m^2 reed canary grass units using synthetic wastewater.

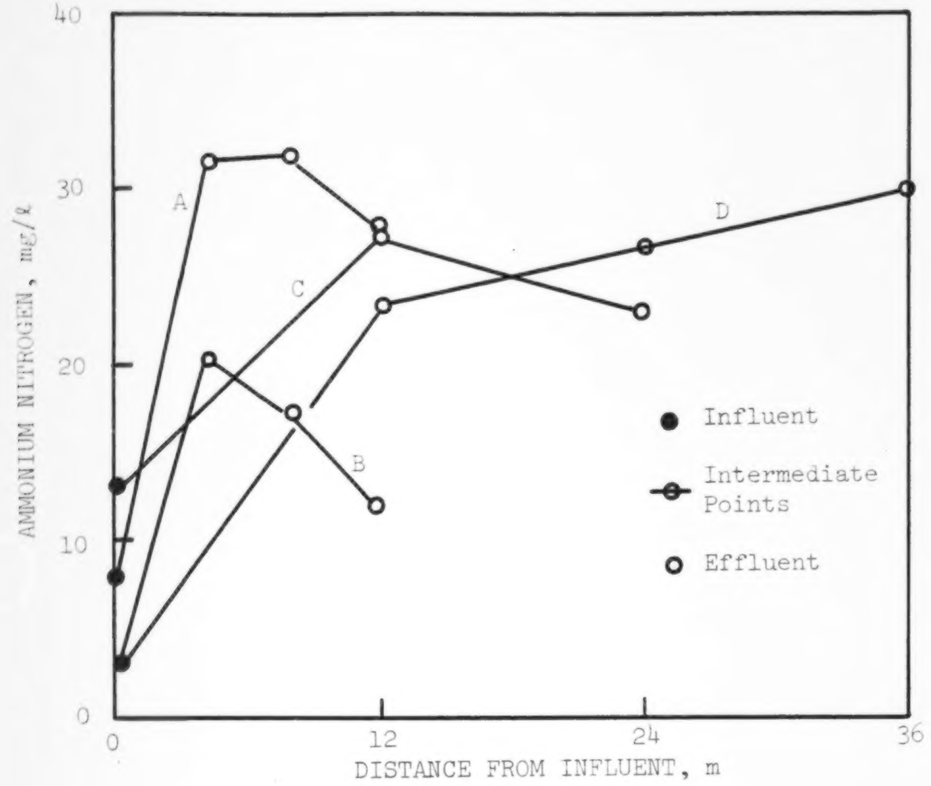


Figure 7.17. Ammonia nitrogen concentrations of synthetic sewage at various sampling points in NFT systems. Curves A and B show 9.3 m² systems at 10.2 and 5.1 cm/d loadings, respectively, while Curves C and D show 18.6 and 27.9 m² systems, respectively, both at loadings of 10.2 cm/d.

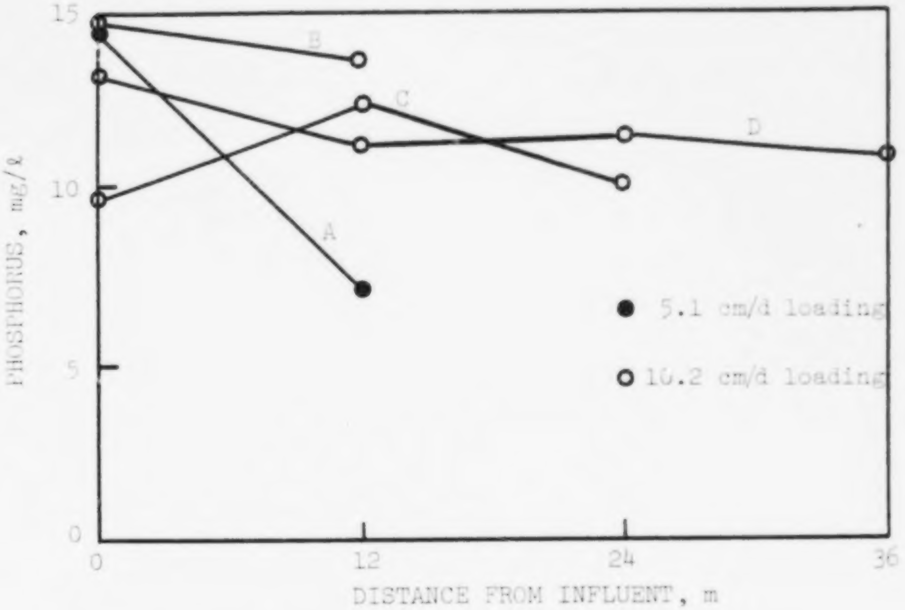


Figure 7.18. Total phosphorus concentrations of synthetic wastewater in different length systems. Curves A and B show the effect of increasing loading. Curves C and D show effect of increasing length on canary grass (C) and multi-species (D) systems.

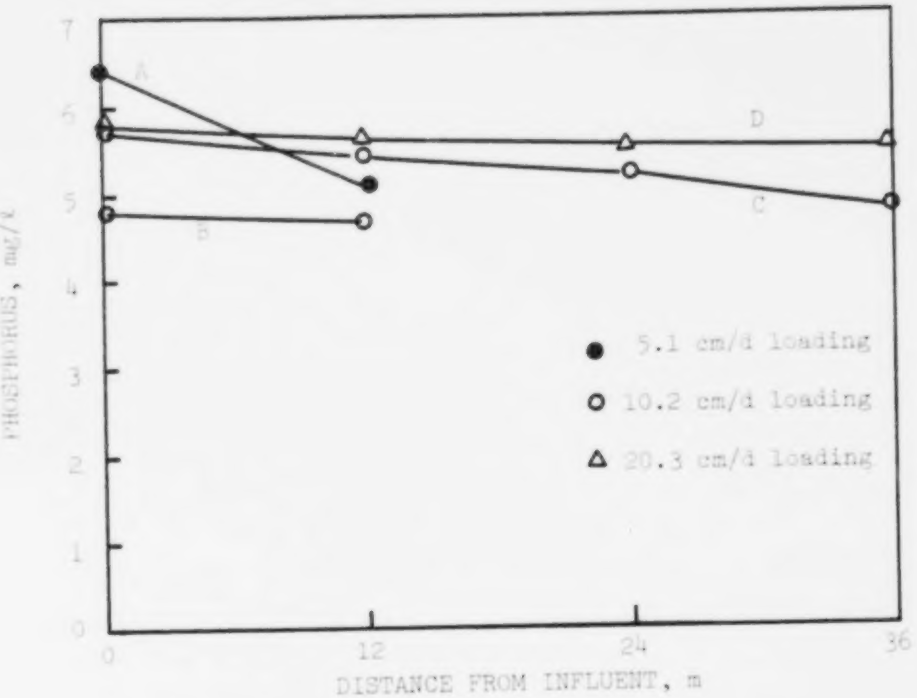


Figure 7.19. Total phosphorus concentrations of domestic sewage at different loading rates to two systems. Curves A and B show a smaller removal at a higher loading for 12 m systems, and Curves C and D show the same for 36 m systems.

removal) of the phosphorus were achieved at many of the loading rates. At increasing loadings of 10 to 20 cm/day the change in phosphorus concentrations decreased to only a little more than 1 mg/ℓ. Figure 7.20 compares the ortho-phospate and total phosphorus concentrations of influent and effluent sewage. There is a consistent difference of a little less than 1 mg/ℓ between total and ortho-phosphorus.

B.9 Indicator Organisms

Fecal coliform analysis was conducted on several samples for the domestic sewage studies. These data show that approximately 90% of the fecal coliform was reduced in one 12-meter length unit. Additional information needs to be developed in this area.

B.10. Zinc and Cadmium

Changes in concentration of zinc in the synthetic wastewater were studied briefly, whereas the removal efficiency of cadmium was studied throughout the testing period. Figure 7.21 summarizes the few observations on zinc removal that were made and indicates an efficient removal at loadings of 5 and 10 cm/day of wastewater. The influence of the loading rate and the length of the unit on the cadmium concentration is shown in Figure 7.22. The influent concentration varied from 0.1 to a little more than 0.3 mg/ℓ and was rapidly reduced within the first few meters of length in the nutrient film to less than 0.06 mg/ℓ in most cases. It is likely that the efficient removal of cadmium is a function both of the anaerobic solids in the root zone and the plant uptake of cadmium in the initial section. The uptake of heavy metals in the influent part of the nutrient film system would have to be examined carefully in terms of ultimate disposal or use of the plant products.

C. PROCESS SENSITIVITY AND POLLUTANT REMOVAL MECHANISM DEFINITION

The data presented in the previous section indicates that the NFT is capable of producing secondary quality or better effluent from primary settled sewage and a soluble synthetic wastewater. This information, however, does not indicate the reasons or the mechanisms responsible for controlling the pollutants or the limitations in the process. This section is intended to summarize the data further and present information on small-scale experiments designed to clarify several pollutant removal mechanisms.

C.1. Hydraulic Retention Time Effects

Perhaps the most critical parameter in controlling pollutant removal in any reaction scheme is the length of time that the pollutant is exposed to the removal mechanism. In the NFT system the hydraulic retention time indicates the duration that the pollutant can be acted upon both by the root system as well as by the entrapped microbial mass. Increased hydraulic retention in the unit can also be an indication of increased depth of liquids, and this will in turn affect the diffusions of oxygen pollutants to the bacteria and the roots. The ability to predict the hydraulic retention time in any given system in which the substrate removal rate is known would allow a unit to be

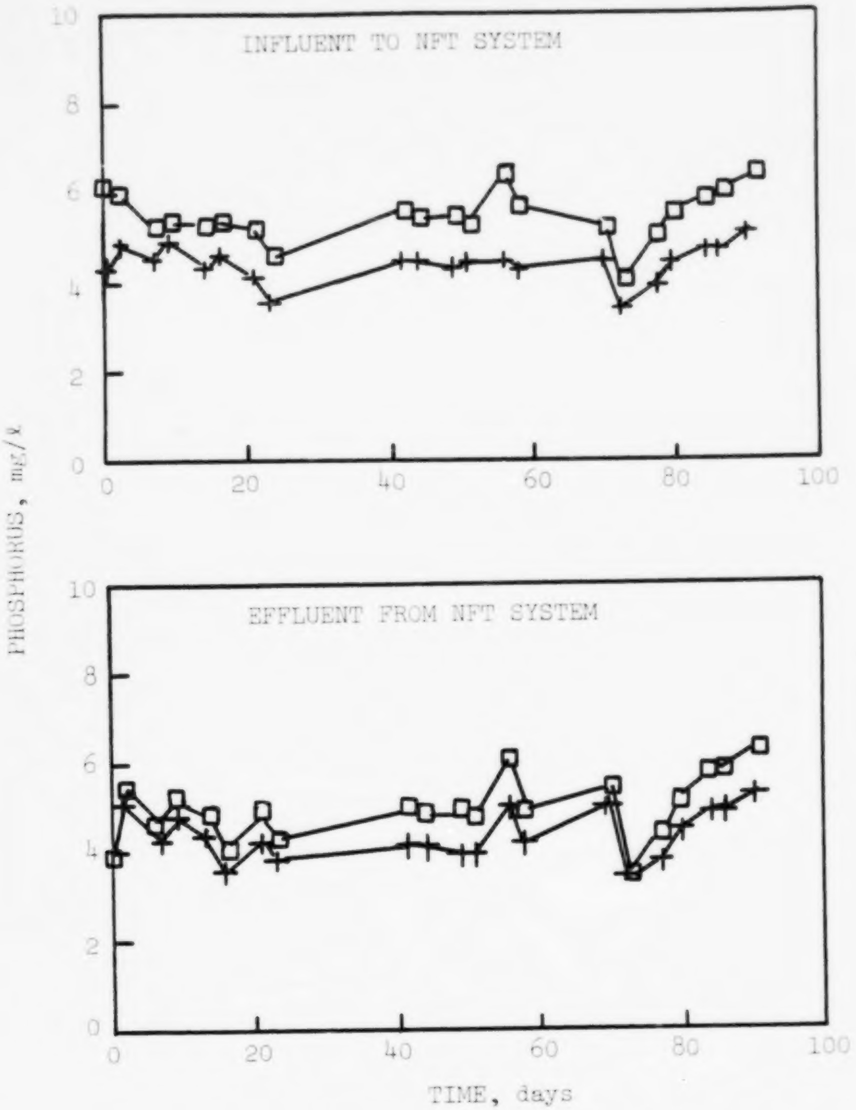


Figure 7.20. Influent and effluent concentrations of phosphorus in domestic sewage in the Hanover NFT system, which began operation on February 16, 1981.

□ = total phosphorus
+ = ortho phosphorus

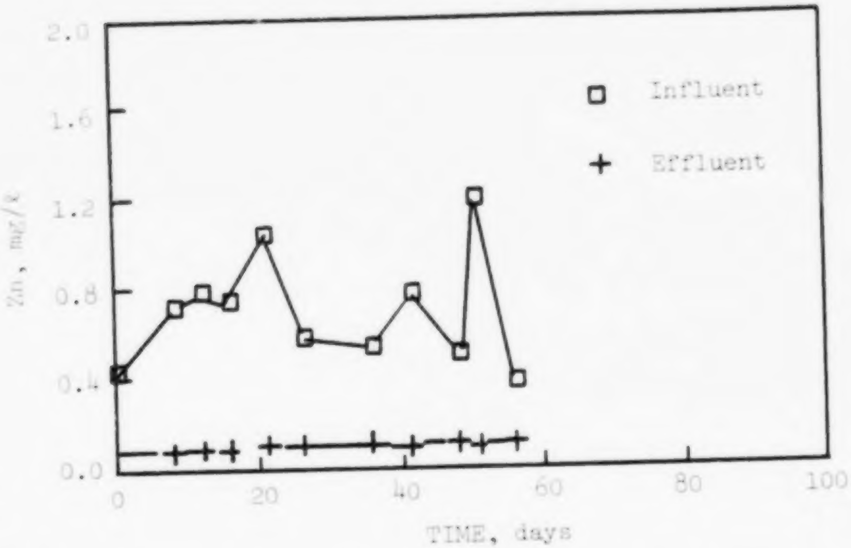


Figure 7.21. Influent and effluent zinc concentrations of synthetic sewage in a reed canary grass pilot scale unit. First day of analysis was July 25, 1980.

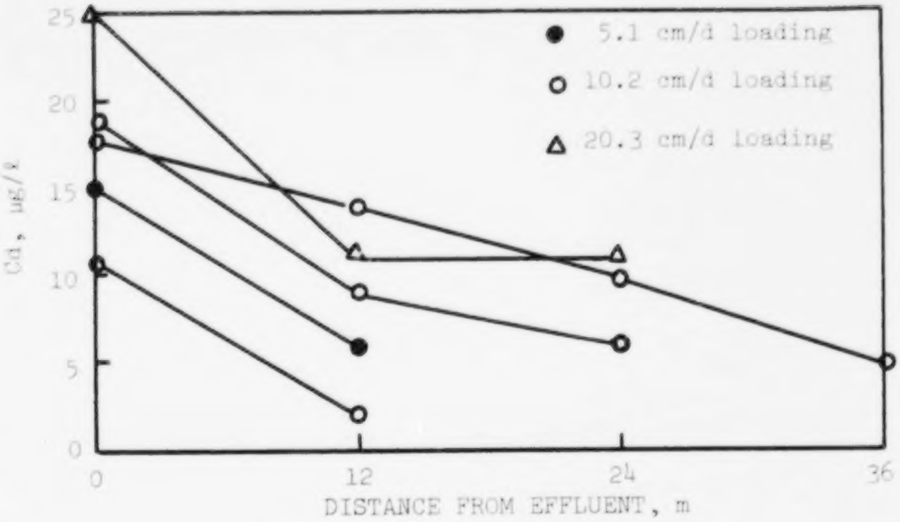


Figure 7.22. Cadmium concentrations of synthetic wastewater in different length systems under several loading conditions. Curves A and B represent 9.3 m^2 units, and Curves C and D represent 18.6 m^2 units. Curve E represents a 27.9 m^2 unit.

designed based on the required hydraulic retention time. Originally, it was thought that increased microbial mass and root mass should increase the hydraulic retention time. This increase in retention time would be a reflection of the advantage of the nutrient film system over other biological contacting systems.

The information shown in Figure 7.23 relates the hydraulic retention time to the hydraulic loading rate in a 36-meter long unit and was obtained from tracer testing with NaCl. Hydraulic retention times at loading rates of 10 cm per day in these units were 100 minutes. Although this should be sufficient time for an organic carbon interaction and suspended solids removal, it is a limited time span for nutrient interactions. This short hydraulic retention time suggests that for specific pollutant removal, such as suspended solids, operation of the unit in a manner that would increase the hydraulic retention time would achieve better efficiency of pollutant removal than was achieved by the semi-continuous operation tested. For example, a decrease in the slope of the unit would result in increased hydraulic retention time. Another method of changing the hydraulic retention time would be to use an intermittently loaded and unloaded unit as if operating a multiple batch operation. Several of these alternatives were tested in short-term experiments with sewage at the Cayuga Heights, New York, treatment facility and are discussed elsewhere.

The effect of maturation of the NFT system on the hydraulic retention time in the system is shown in Figure 7.24. This indicates that the hydraulic retention time may double as the root mass and the suspended solids increase. Although this is valid, it has a loading rate limitation, as will be shown in short-term studies. Application of high loading rates on mature systems actually results in a shorter retention time, most likely because of a short-circuiting that occurs after the suspended solids are entrapped in complex root mass. Additional work will be needed in the area of hydraulic retention time to define the influence of root mass and solids accumulation on this important parameter.

C.2. Loading Rate Effects

There are four loading rate parameters that need to be considered in defining this process. First is the hydraulic, or area, loading rate, which is the equivalent depth of wastewater applied to the surface area of the system over a day's time (measured as centimeters per day). Second are mass loading rates of nutrients or pollutants in terms of mass of constituent added to the reactors per unit area of the system (measured as kilograms per square meter per day). Third is the weir loading rate, or the volume of wastewater added to the system divided by the width or cross-sectional area (measured as liters per meter of width per day). Fourth is the overflow rate which is similar to upflow velocities that occur in a clarifier. (The weir loading in terms of cubic meter per meter width of the unit results in the average liquid velocity that would occur in a clarifier where the surface area is the area of the NFT unit).

If empirical relationships could be developed between treatment performance and loading rates, it would provide a highly simplified method of sizing NFT

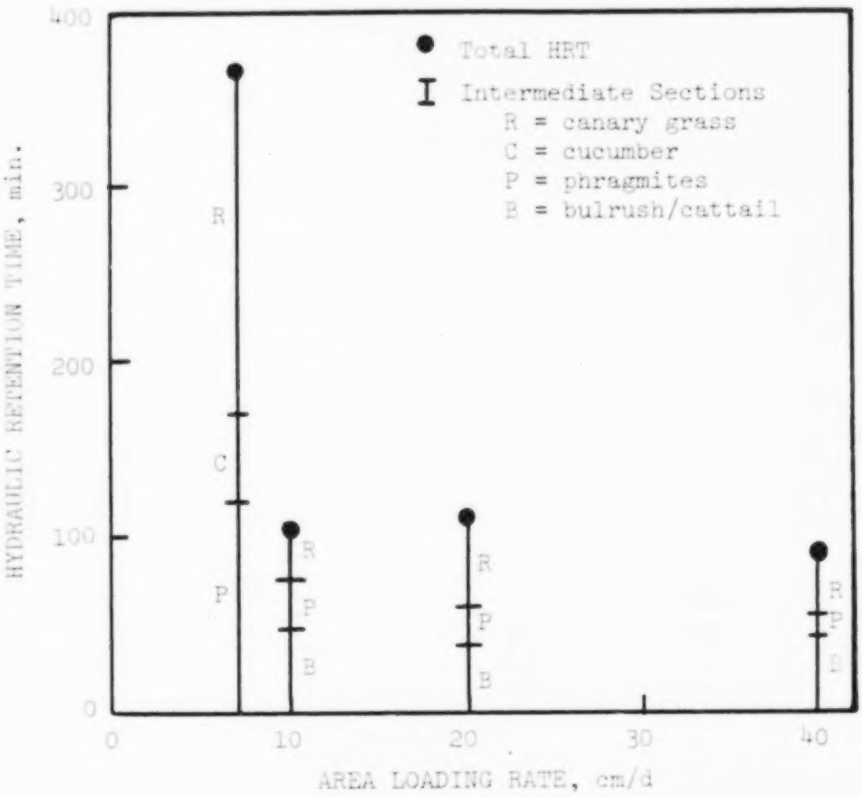


Figure 7.23. Hydraulic retention times of a 36 m NFT system using synthetic wastewater.

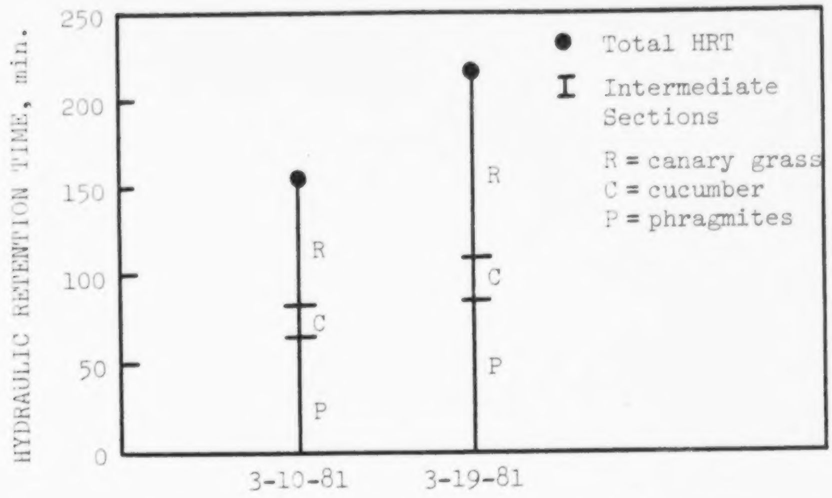


Figure 7.24. Hydraulic retention time of the 36 m system using domestic wastewater loaded at 10.2 cm/d.

systems. The hydraulic retention time masks the effects of many parameters such as pollutant concentration; however, if there is a loading rate relationship between the hydraulic addition and the effluent quality, it provides the simplest method of sizing the system. It is more likely that the mass loading rates will be easier to manipulate in empirical relations since the pollutant removal mechanismswill be more closely related to the amount of the pollutant added per system area per unit time. Other variables such as suspended solids, may be more easily explained by weir loading rates than mass loading rates since they are removed by the physical process of sedimentation. The weir loading rate is directly related to the hydraulic velocities in the system. Typical results achieved with the steady-state conditions with the synthetic and domestic sewage systems are presented in the following sections.

C.3. Loading Rate Relationships with Synthetic Wastewater

The ranges of pollutant mass loading rates, steady state mass removal rates and removal efficiencies for pilot scale system tests with synthetic sewage are summarized in Table 7.2. Hydraulic loading rates varied from 5.1 to 40.6 cm/d over the testing period, with most rates around 10 cm/d (see Table 6.12). Detailed tables showing specific loading rate data are presented later (Table 7.22).

TABLE 7.2. RANGE OF POLLUTANT LOADING RATES TESTED WITH SYNTHETIC SEWAGE IN PILOT NFT UNITS. TARGET HYDRAULIC LOADING RATES VARIED FROM 5.1 to 40.6 cm/d.

Parameter	Range of Measured Mass Loading Rate kg/ha-d	Range of Observed Steady State Removal Rate kg/ha-d	Range of Pollutant Removal Efficiency % of Added
COD	133-972	46-414	32-91
Soluble COD	101-903	87-461	51-88
N	13-141	5- 20	6-57
P	6- 50	0- 4	1-52
Cd	0.020-0.509	0-0.285	0-91

Chemical oxygen demand removal efficiency showed a small effect of loading rate, but COD treatment was also affected by other factors as well. Figure 7.25 shows the relation between treatment efficiency and mass loading rate, and it indicates that a wide range of efficiencies occurred at some relatively low loading rates. Hydraulic retention time appeared important in characterizing COD removal, and HRT relationships will be presented later. In addition, temperature and radiation appeared important in COD removal. Removal rates compared to loading rates are shown in Figure 7.26, which also shows the small effect ($r^2 = .36$) of loading rate.

Since the synthetic sewage was composed of soluble rather than particulate or colloidal material, little difference was expected between total and soluble COD. This was generally the case, as Figure 7.27, which describes mass

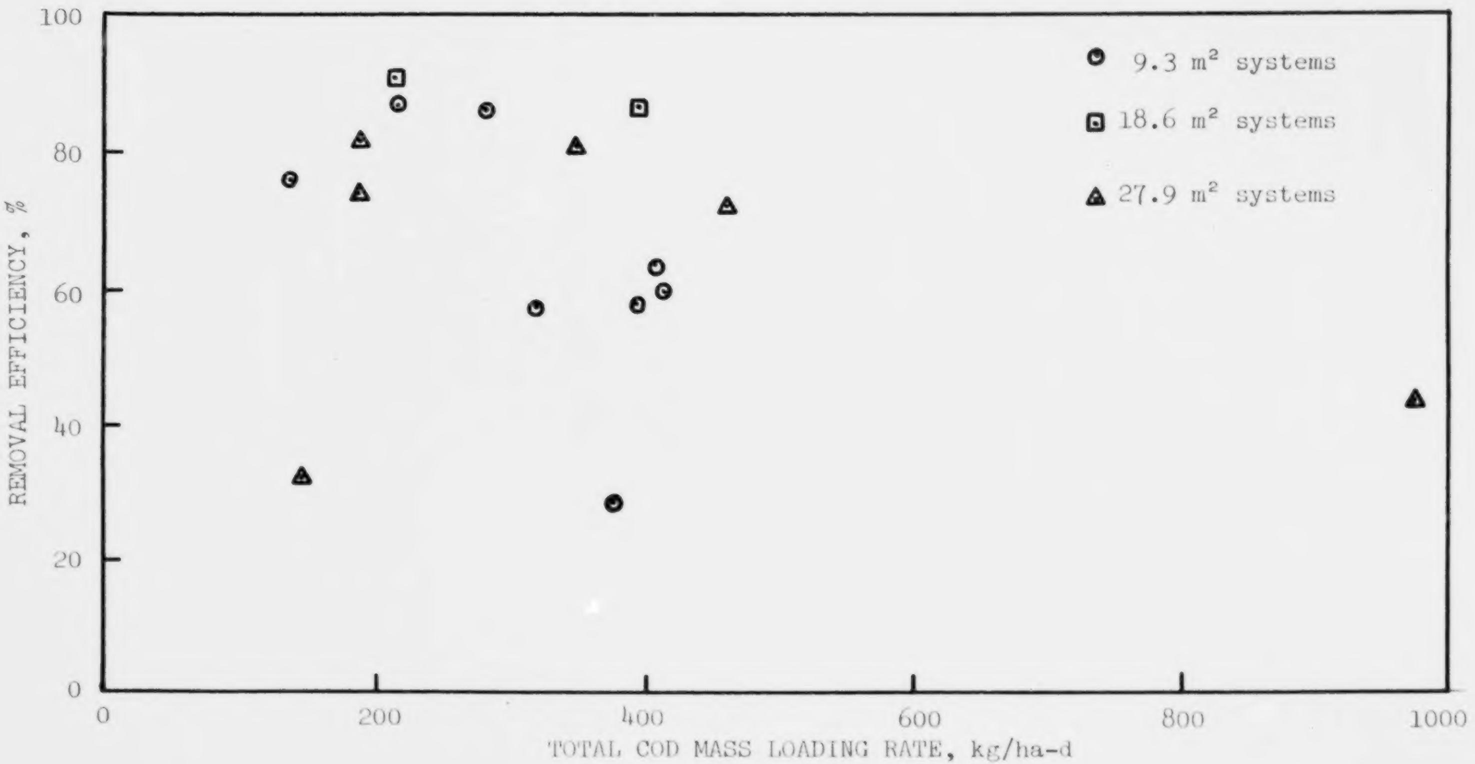


Figure 7.25. Relationship between total COD removal efficiency and total COD mass loading rate for conditions tested with synthetic sewage.

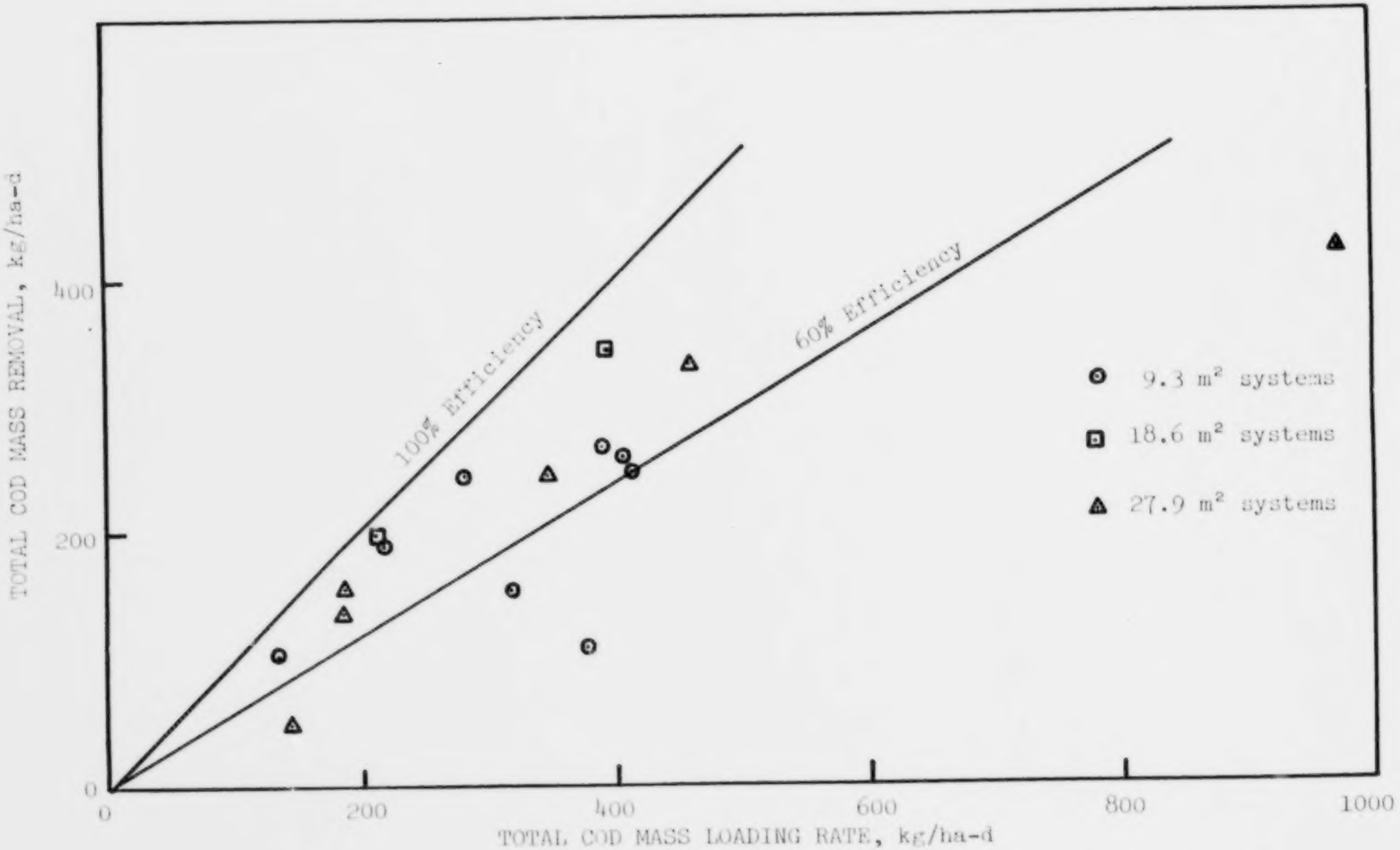


Figure 7.26. Relationship between total COD mass loading rate and total COD mass removal in the NFT systems treating domestic sewage.

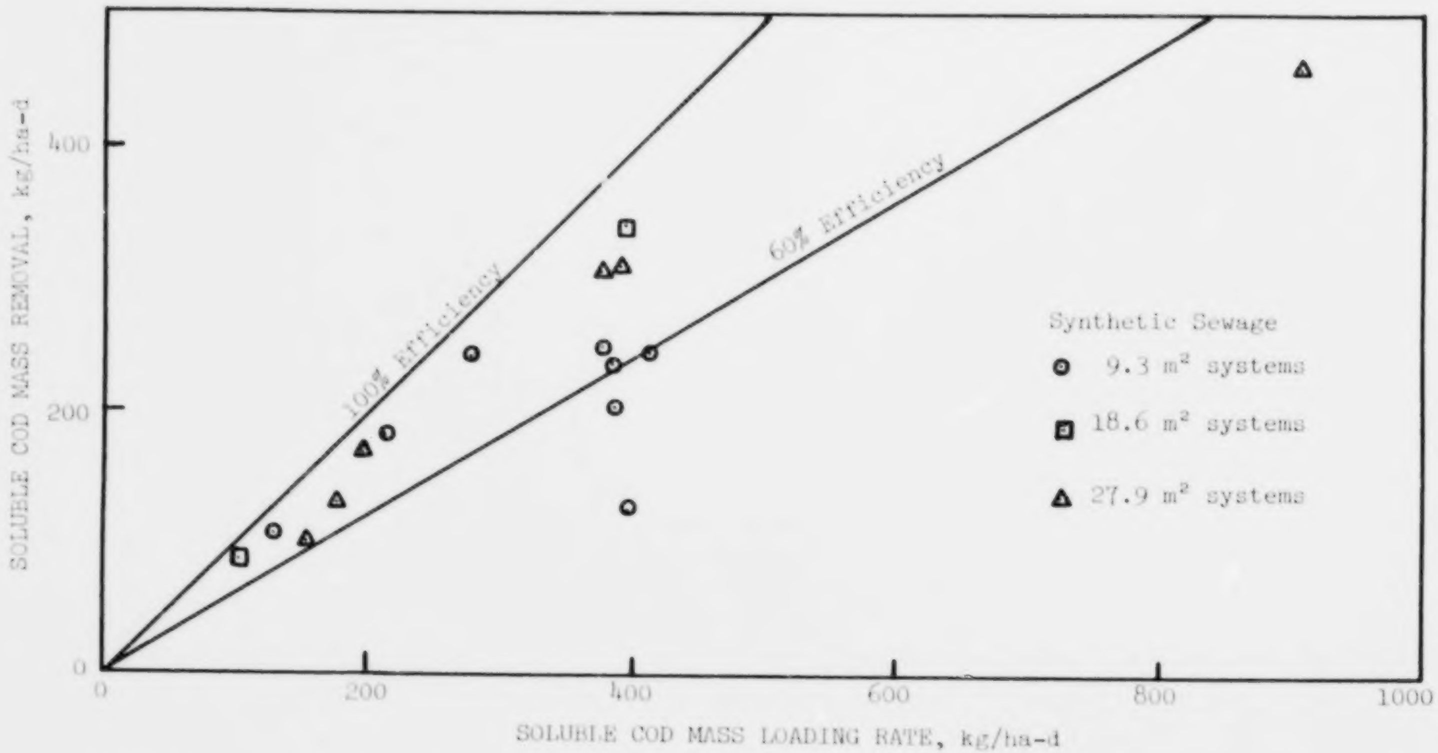


Figure 7.27. Relationship between soluble COD mass loading rate and soluble COD mass removal in the NFT systems treating synthetic sewage.

removals of soluble COD, closely parallels removals shown in Figure 7.26. Total COD was slightly higher than soluble COD in the effluent, indicating that some solids generation had occurred in the systems.

Total nitrogen showed an inverse relationship with nitrogen loading (r^2 = .24). Figure 7.28 shows removal efficiency of N as a function of N loading for three different size systems. Soluble nitrogen showed the same trend, with a higher correlation (r^2 = .56) as shown in Figure 7.29. Further analysis of N will be presented in Section 7.E.

Phosphorus efficiency was scattered in general, but followed a rough inverse relationship also. Figure 7.30 shows total phosphorus removal as a function of P loading rate (r^2 = .30). Similarly, Figure 7.31 shows this relationship for soluble P (r^2 = .16). Other factors such as oxidation reduction potential are important for P control and will be discussed later.

C.4. Primary Settled Domestic Sewage Loading Rates Effects

The range of mass loading rates, mass removal rates, and process efficiencies examined with sewage in the 4 to 20 cm/day loaded units are summarized in Table 7.3. Maximum treatment efficiencies for BOD and suspended solids exceeded 90% whereas the maximum removal of nutrients was always less than 30%. The temperature, time of year, irradiation and sewage concentration values are significant factors in the efficiency of the process. Figure 7.32 shows the relationship between BOD treatment efficiency and loading rate for all of the steady conditions examined in this study. This figure indicates that there appears to be a good relationship between removal efficiencies and loading rate. The observed BOD removal rates in relation to the loading rate are shown in Figure 7.33. As the figure indicates, the NFT process is quite efficient at loading rates of up to 200 kilograms per hectare per day. Such a relationship does not follow as closely for the TOC although there are limited data as shown in Figures 7.34 and 7.35.

Similar loading rate relationships for total and volatile suspended solids are shown in Figures 7.36 and 7.37. High treatment efficiencies of suspended solids were achieved at loading rates exceeding 200 kilograms per hectare per day.

The loading rate-removal efficiency relationships of nitrogen and phosphorus are more scattered (see Figures 7.28, 7.38 and 7.39). Although there appears to be a relationship, it will be necessary to consider plant uptake and other mechanisms before NFT nutrient removal can be defined.

All of the data for sewage temperature were examined to determine whether it was a significant variable with the sewage system. The operation of the units in the winter climate in western New Hampshire gave us an opportunity to examine the temperature and light limitations on the NFT process. The following figures show the effect of influent sewage temperature on BOD and total organic carbon (Fig. 7.40), suspended solids (Fig. 7.41), and nitrogen and phosphorus (Fig. 7.42). These data indicate that there is no influence of temperature on these pollutant removal mechanisms, possibly because only a small range of temperatures was experienced. Although the influent

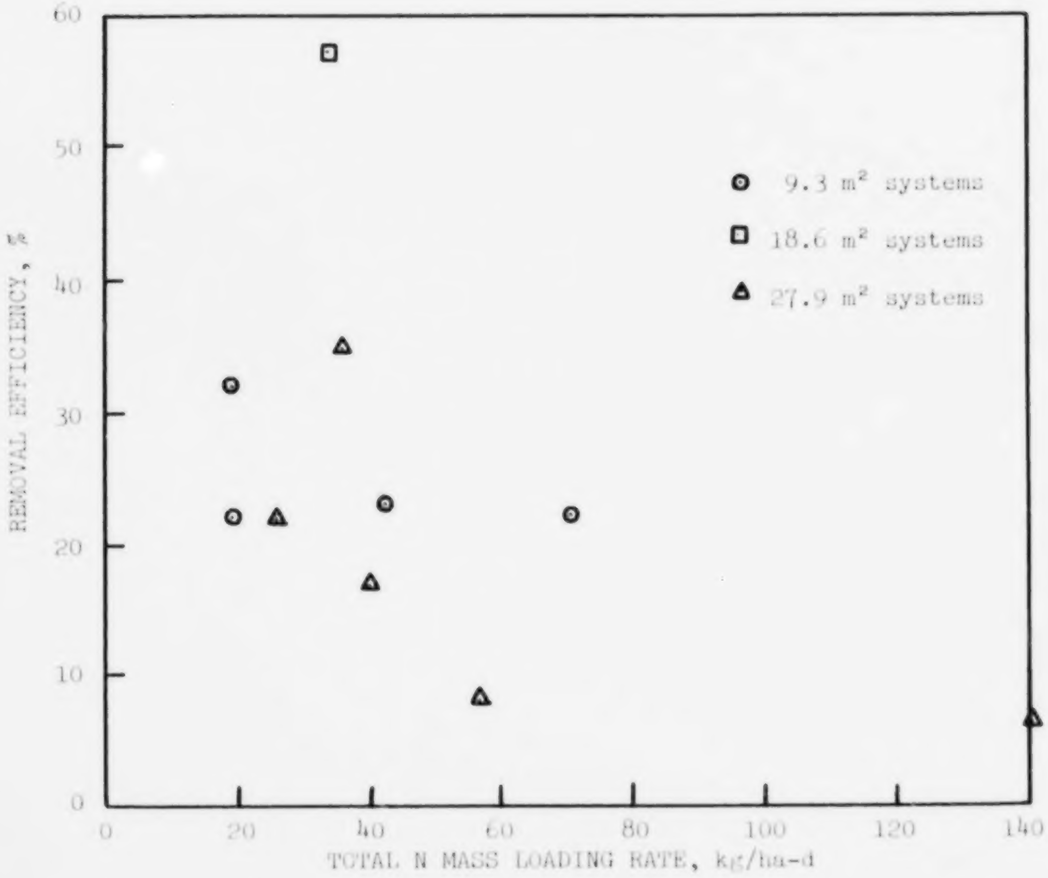


Figure 7.28. Relationship between total nitrogen removal efficiency and total nitrogen mass loading rate for conditions tested with synthetic sewage.

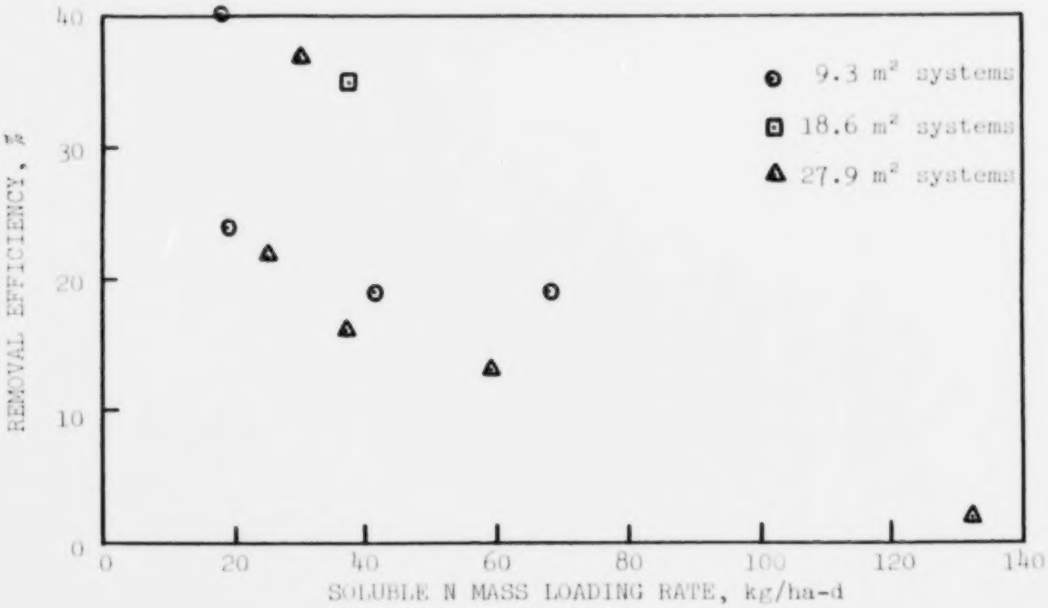


Figure 7.29. Relationship between soluble nitrogen removal efficiency and soluble nitrogen mass loading rate for conditions tested with synthetic sewage.

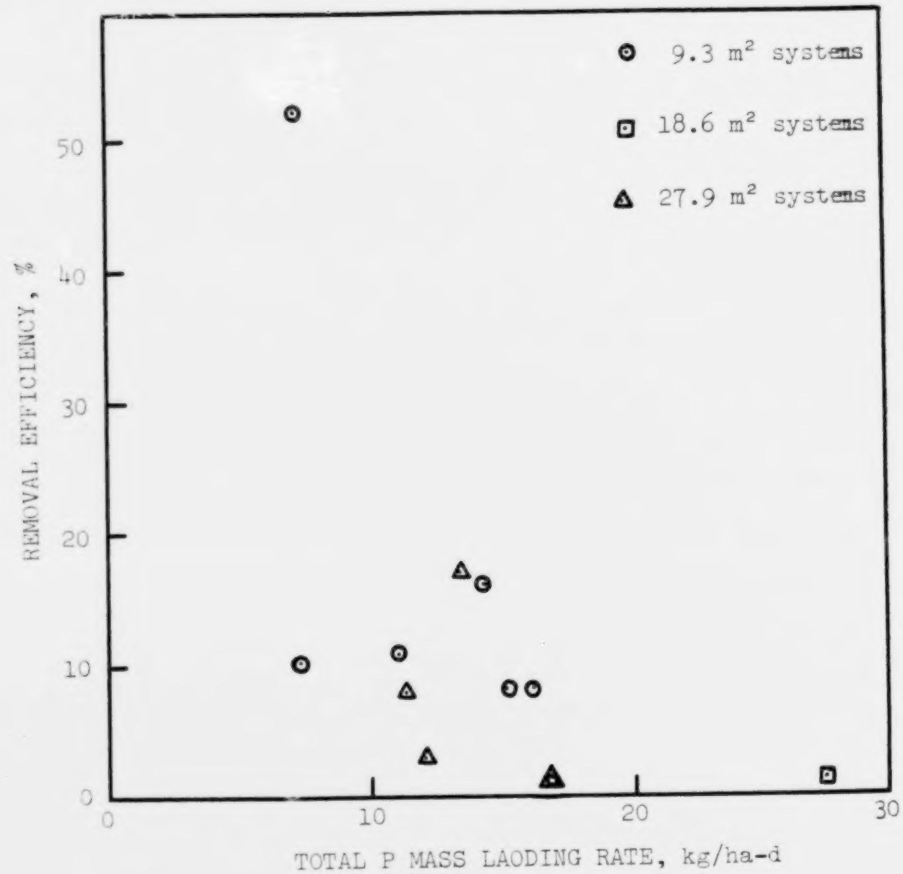


Figure 7.30. Relationship between total phosphorus removal efficiency and total phosphorus mass loading rate for conditions tested with synthetic sewage.

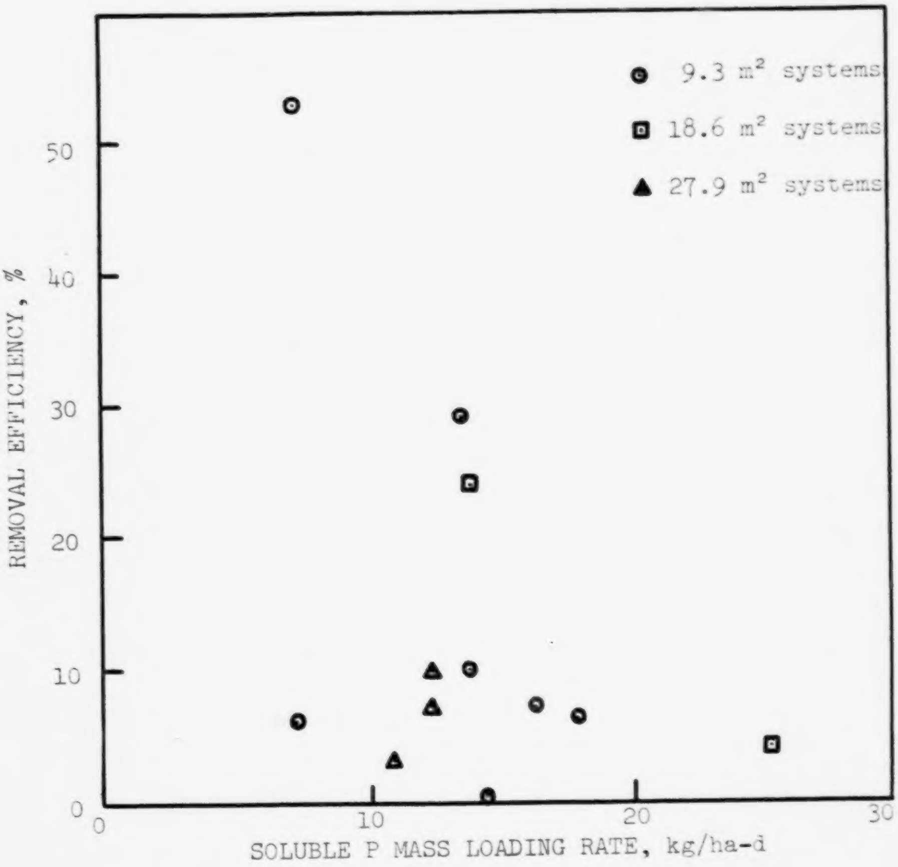


Figure 7.31. Relationship between soluble phosphorus removal efficiency and soluble phosphorus mass loading rate for conditions tested with synthetic sewage.

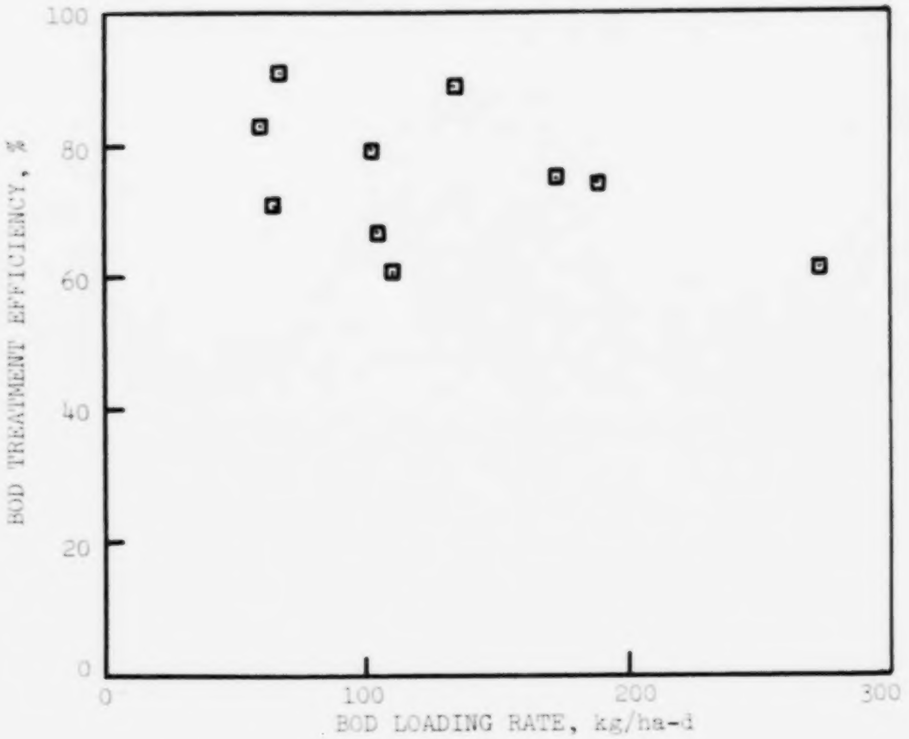


Figure 7.32. Relationship between BOD removal efficiency and BOD mass loading rate for conditions tested with domestic sewage.

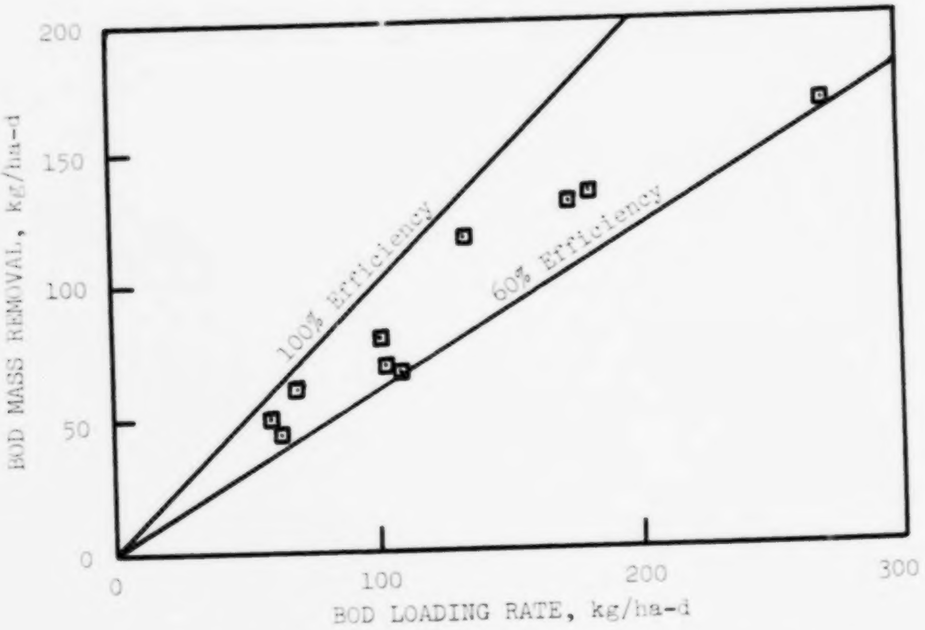


Figure 7.33. Relationship between BOD mass loading rate and BOD mass removal in the NFT systems treating domestic sewage.

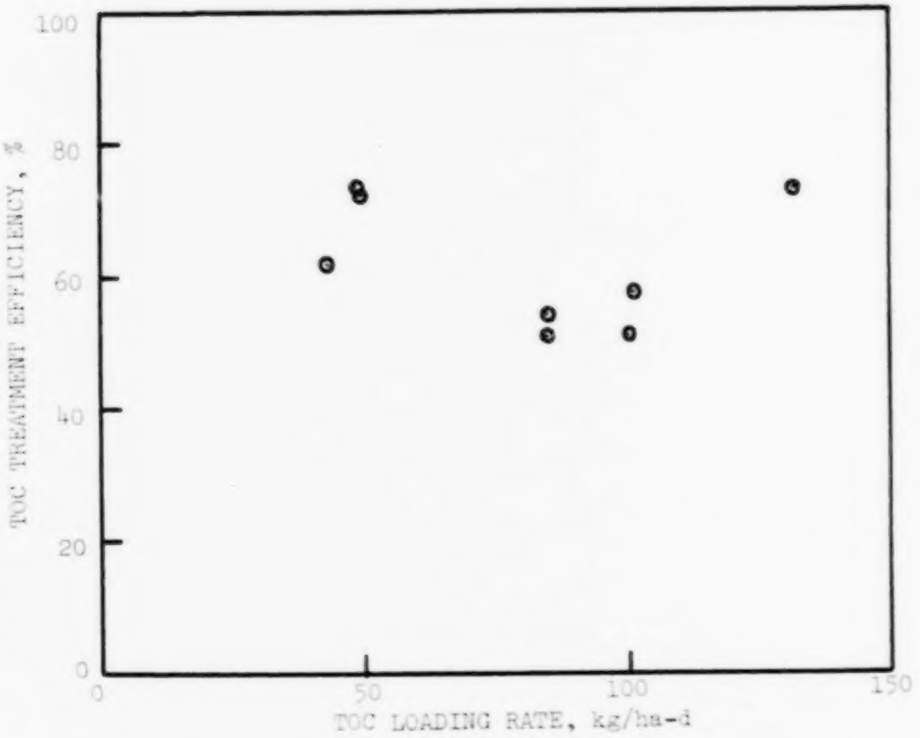


Figure 7.34. Relationship between TOC removal efficiency and TOC mass loading rate for conditions tested with domestic sewage.

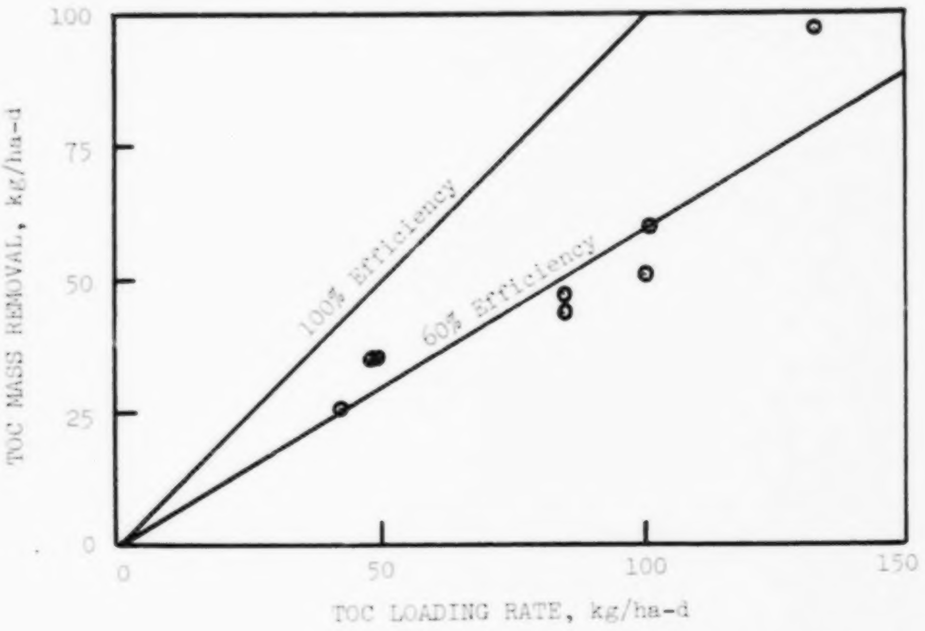


Figure 7.35. Relationship between TOC mass loading rate and TOC mass removal in the NFT systems treating domestic sewage.

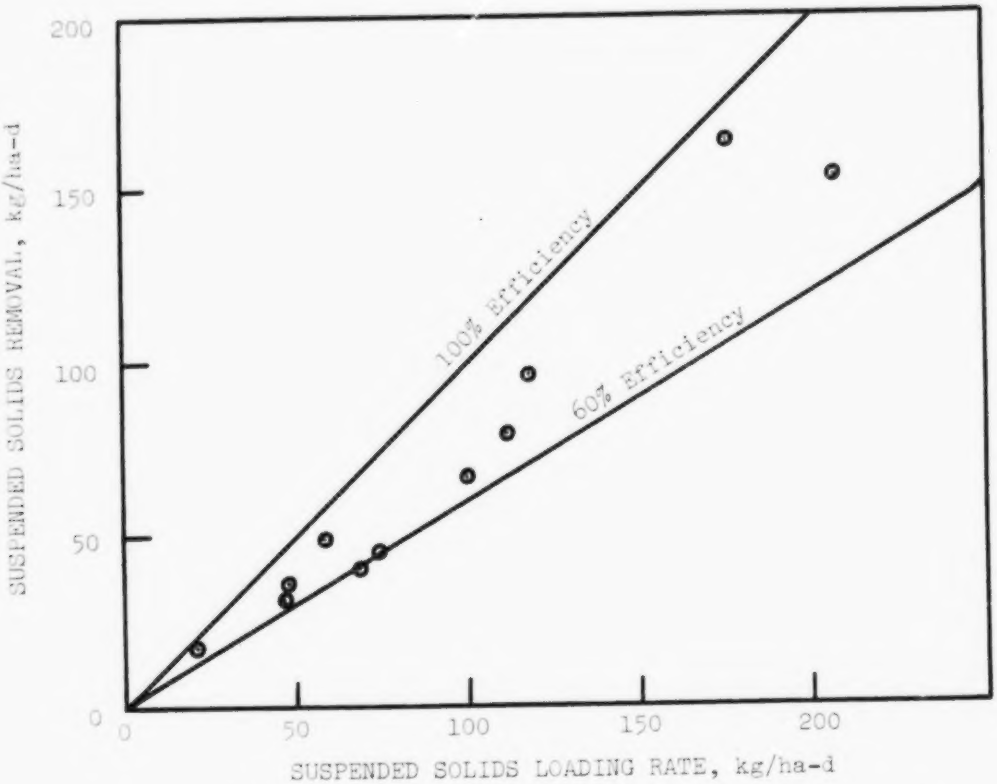


Figure 7.36. Relationship between suspended solids mass loading rate and suspended solids mass removal in the NFT systems treating domestic sewage.

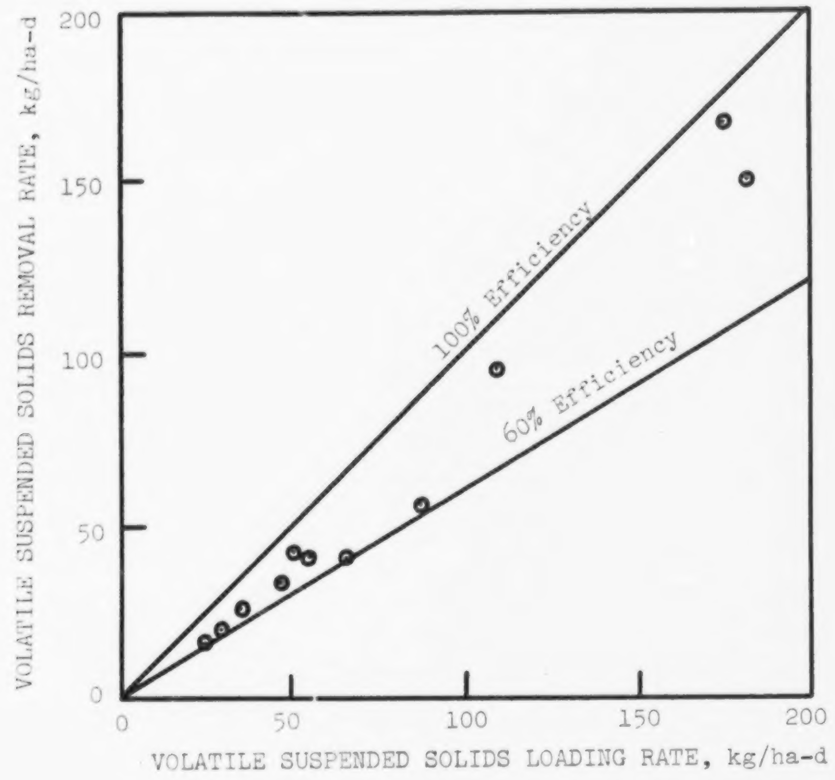


Figure 7.37. Relationship between volatile suspended solids mass loading rate and volatile suspended solids mass removal in the NFT systems treating domestic sewage.

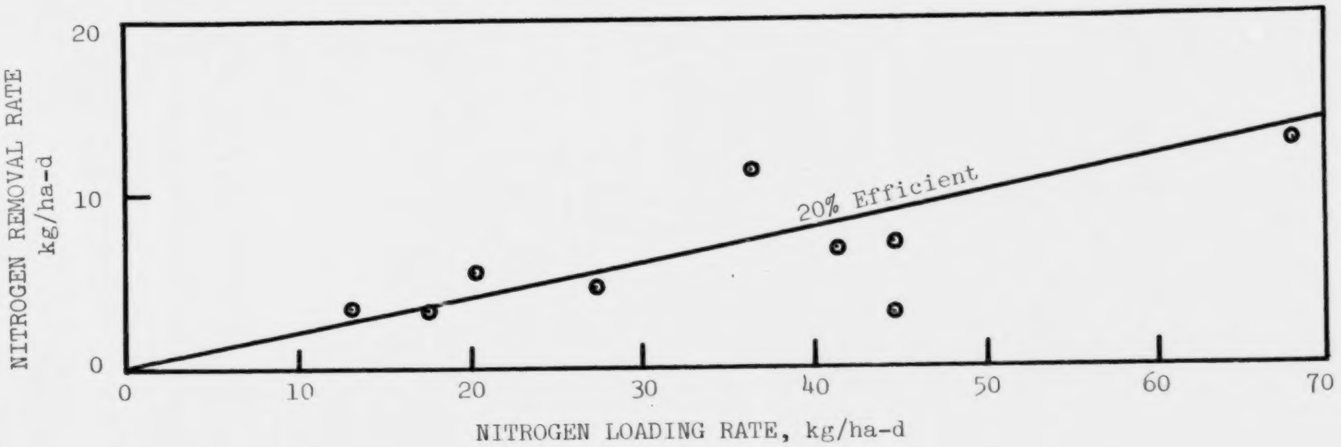


Figure 7.38. Relationship between nitrogen mass loading rate and nitrogen mass removal for conditions tested with domestic sewage.

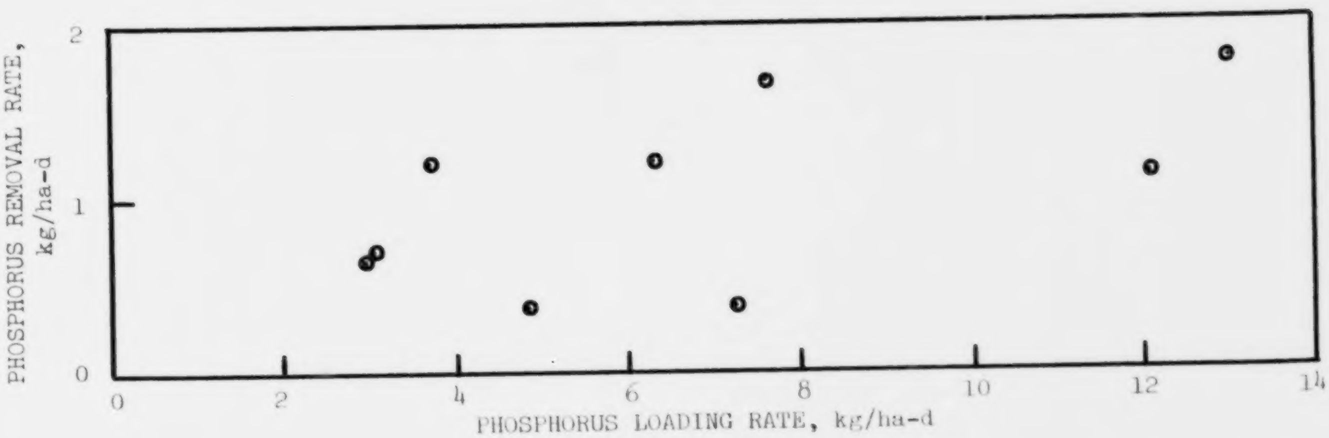


Figure 7.39. Relationship between phosphorus mass loading rate and phosphorus mass removal for conditions tested with domestic sewage.

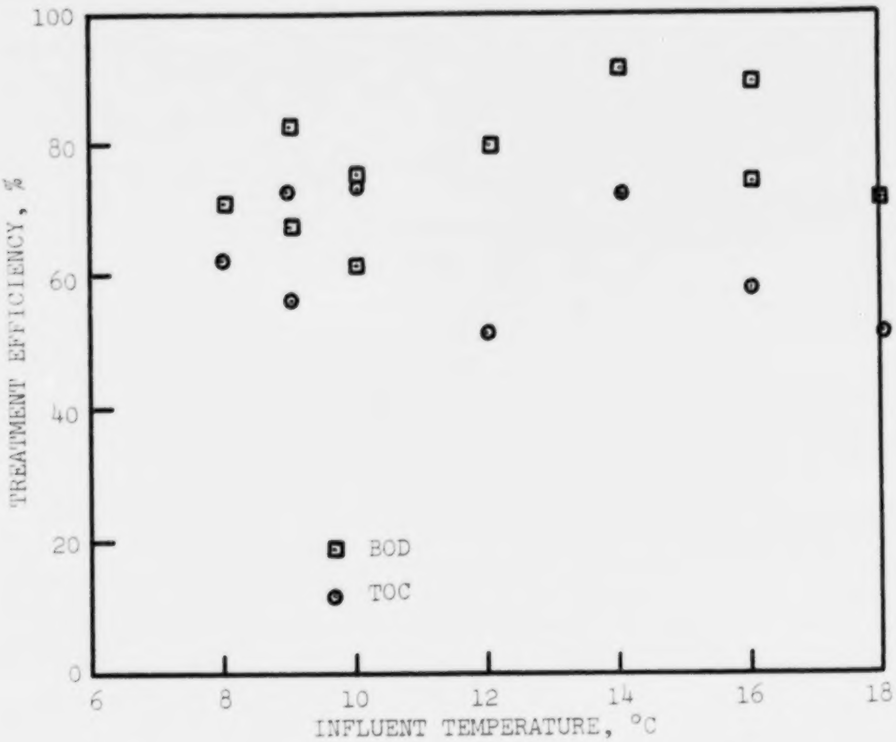


Figure 7.40. Effect of temperature on the treatment efficiency of BOD and TOC in NFT systems using domestic sewage.

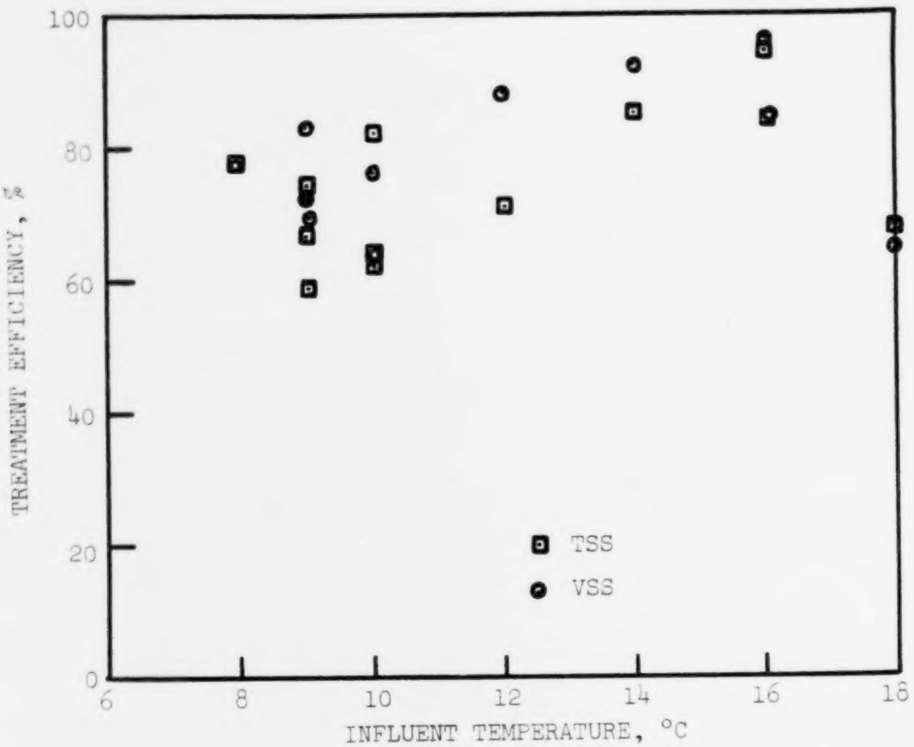


Figure 7.41. Effect of temperature on the treatment efficiency of total and volatile suspended solids in NFT systems using domestic sewage.

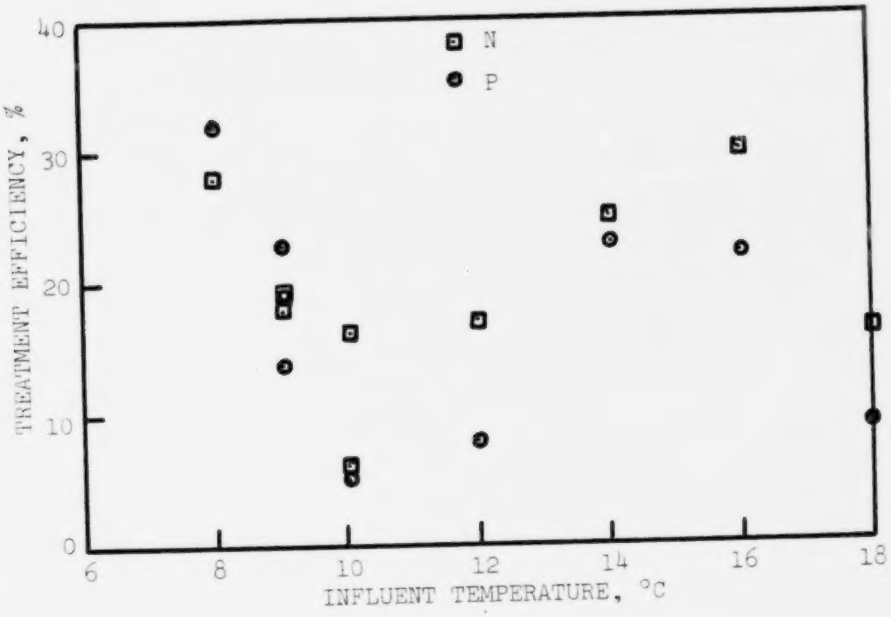


Figure 7.42. Effect of temperature on the treatment efficiency of nitrogen and phosphorus in NFT systems using domestic sewage.

TABLE 7.3. RANGE OF POLLUTANT LOADING RATES TESTED WITH DOMESTIC SETTLED SEWAGE IN PILOT NFT UNITS. TARGET HYDRAULIC LOADING RATES VARIED FROM 5.1 to 20.3 cm/d IN PILOT UNITS, WITH INTERMEDIATE LOADING RATES OF GREATER THAN 200 cm/d. ONLY THE TOTAL UNIT RESULTS ARE SHOWN HERE.

Parameter	Range of Measured Mass Loading Rate kg/ha-d	Range of Observed Steady State Removal Rate kg/ha-d	Range of Pollutant Removal Efficiency % of Added
BOD	58-272	44-166	61-91
TOC	42-132	26- 97	51-73
COD*	133-556	99-247	44-74
SS	20-206	17-164	59-94
N	13- 68	2.8-12.7	6-30
P	2.97-13.0	0.38-1.77	5-32

*Limited amount of data

temperature ranged to less than 7°C, the collection of solar energy in the plastic greenhouse raised the sewage temperature to 14 to 15°C for a significant portion of the day in all cases. Thus the temperature differentials between summer operation and winter operation were usually less than 10°C and often only 5° or 6°C. This effect was apparent on a cold day. When the outside air temperature was minus 20°C, the average influent sewage temperature to the greenhouse was 7°C; and the effluent sewage temperature was often around 22°C.

C.5. Plant Environmental Factors

A number of factors were anticipated to influence plants in such a way that it would make them of limited value for wastewater treatment in the NFT. Dissolved oxygen concentrations, temperature, and light intensities all have the capability of controlling plant health and growth rate. The dissolved oxygen concentrations in units heavily loaded with BOD were low. Reed canary grass grew poorly, and patches of it died when area loading rates were significantly greater than 20 cm per day. It appeared that this loading rate would eventually kill all the reed canary grass. Figures 7.43 and 7.44 show the differences between a healthy stand of reed canary grass and the condition of reed canary grass after a long period of application at loading rates of 20 cm per day with synthetic wastewater. Similar observations were made during domestic sewage applications. In both domestic and synthetic sweage, when the loading rates were decreased or eliminated, the grass recovered rapidly. In one series of experiments the reed canary grass was allowed to turn completely brown. Subsequent additions of tap water enabled the reed canary grass to recover over a period of several weeks. After this period of time the grass appeared to be normal. Thus the influence of overloading has the capability to damage the grass, but it is possible for it to recover when loading rates are relaxed.

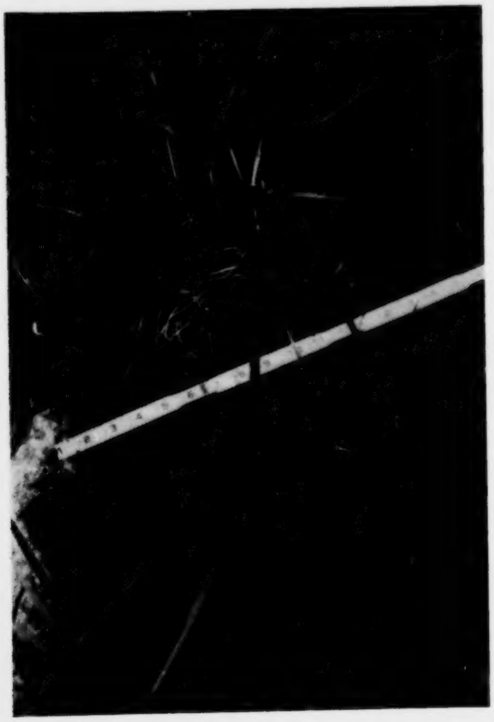


Figure 7.43. **Healthy canary grass in Unit 3, Bracehouse.**

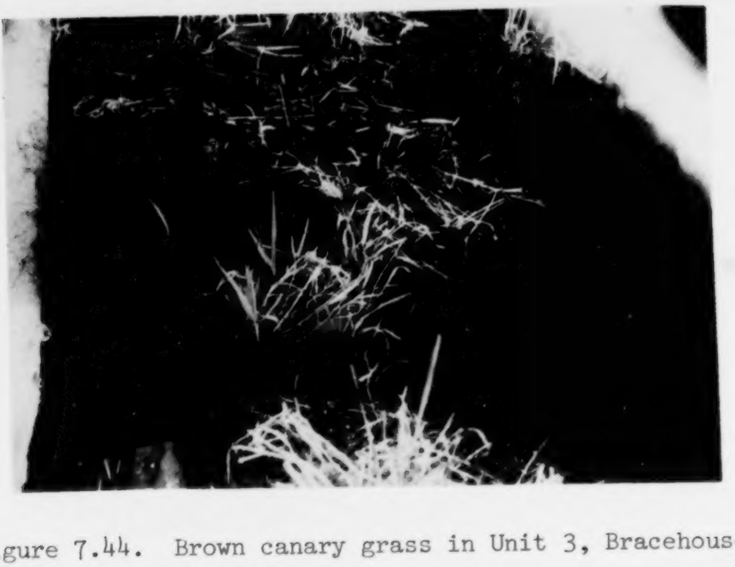


Figure 7.44. Brown canary grass in Unit 3, Bracehouse.

Napier grass was found to be particularly sensitive to low dissolved oxygen levels. In one series of experiments the liquid flow was eliminated and the napier grass was allowed to stand for about 24 hours in a non-aerated water with the roots submerged in 20 cm of water. The apparent lack of oxygen to the root system caused death of the napier grass. Subsequent tests where the napier grass was inundated with 15 cm or more of water for shorter periods did not have this effect. Plants known to be capable of surviving an anaerobic root zone such as cattails, bulrushes and sedges were affected little by high organic loading rates and low D.O. when roots were completely inundated by water and solids.

Additional information on factors affecting plants is presented in Section 7.F on plant culturing.

C.5.a. Temperature—

The temperature of the wastewater, as indicated earlier, had a relatively minor effect within the range tested. However, the combination of season, light intensity and temperature did have a significant impact on one species, phragmites. Phragmites has the characteristic of dying back when the photoperiod is sufficiently shortened. During several months of the winter, the NFT sections of phragmites appeared to be dead; however, inspection of the roots showed that they were living. As soon as the daylight period increased past the threshold for growth, the phragmites rapidly developed new shoots and started to grow again. The influence of this kind of plant on a waste treatment system would need to be carefully evaluated. The BOD and suspended solids removal might continue during the cold period as long as the roots survived.

C.6. Root Mass Influence

The roots on many of the species tested developed into large masses on the impermeable surfaces of the NFT units. Root depths of greater than 5 cm with phragmites and reed canary grass were common after several months of growth. More dense and deeper roots were achieved with the napier grass, where 10 cm or deeper mats were observed. Although solids were entrapped in the root mass, the effect of root growth on entrapment of solids was not as significant as had been anticipated. In many cases the flocculated solids in the sewage system appeared to be "light and fluffy" and often floated to the top of the roots rather than being entrapped within them. Due to the destructive nature of sampling to obtain root mass determinations, little data in this area were developed. However, a non-destructive technique to measure entrapped solids was developed and used throughout much of the study with the synthetic wastewater and the domestic sewage studies. Examples of the accumulation of total and volatile solids are shown in Table 7.4. Typical entrapped mass solids equalled one thousand grams per square meter of reactor. It is interesting to note that at a liquid standing depth of 5 cm this results in a concentration of entrapped mass of approximately 20 grams per liter. Even if the liquid depth were 10 cm this would be equivalent to 10 grams per liter of entrapped solids. This high concentration of solids indicates the potential that the system has to manipulate the pollutants if it were possible to manage these entrapped solids efficiently.

TABLE 7.4. TOTAL AND VOLATILE ACCUMULATIONS OF MATERIAL IN THE ROOTS OF PLANTS TESTED IN 27.9 m^2 PILOT UNITS USING SYNTHETIC AND DOMESTIC WASTEWATER. VALUES ARE g/m^2. VOLATILE VALUES ARE PARENTHESIZED.

Sewage Type	Species	Distance From Influent End of Unit m	Area Loading Rate, cm/d		
			10.2	20.3	40.6
Synthetic	Cattail/ Bulrush	3	1113(156)	921(359)	510(372)
		6	----	909(409)	642(411)
		11	101(101)	424(305)	448(354)
	Phragmites	3	17(8)	264(203)	670(529)
		6	----	150(78)	404(314)
		11	199(76)	404(267)	624(487)
	Canary Grass	3	1057(772)	899(611)	2119(1526)
		6	----	568(409)	528(370)
		11	956(717)	687(467)	323(174)
			Area Loading Rate, cm/d		
			6.9	10.2	20.3
Domestic	Cattail/ Bulrush	3	----	745(477)	766(230)
		6	824(313)	1044(73)	275(102)
		11	----	562(450)	774(294)
	Phragmites	3	----	507(451)	267(174)
		6	86(52)	1191(107)	90(50)
		11	----	559(492)	211(137)
	Canary Grass	3	----	3705(3520)	982(638)
		6	1008(625)	6423(385)	622(354)
		11	----	4955(297)	998(599)

Table 7.5 converts the data for entrapped solids to an accumulation rate for solids for the various applications and various loading rates tested with the pilot units. There appears to be little accumulation with increased loading rates as shown by the variability of the data. Typical accumulation rates of 20 to 30 grams per m^2/day were observed in the lower loading rates.

C.7. Bench Scale Simulation

An attempt was made to develop a short term test that would simulate the NFT and enable the kinetics of pollutant removal to be more carefully defined with various plant species. In effect, an equivalent to the BOD bottle test was sought to measure the pollutant removal capabilities of the NFT system. Short term, small unit studies using two meter long by 10 cm wide units were

TABLE 7.5. TOTAL AND VOLATILE ENTRAPPED SOLIDS IN THE ROOT ZONE OF PLANTS TESTED IN 27.9 m^2 PILOT UNITS USING SYNTHETIC AND DOMESTIC WASTEWATER. VALUES ARE g/m^2-d. VOLATILE VALUES ARE IN PARENTHESES.

Sewage Type	Species	Distance From Influent End of Unit m	Area Loading Rate, cm/d		
			10.2	20.3	40.6
Synthetic	Cattail/ Bulrush	3	74(10)	35(14)	31(19)
		10.7	7(3)	16(12)	22(18)
	Phragmites	3	----	11(8)	34(26)
		10.7	12(5)	16(11)	31(24)
	Canary Grass	3	53(39)	43(29)	106(76)
		10.7	48(36)	33(22)	16(9)
			Area Loading Rate, cm/d		
			6.9	10.2	20.3
Domestic	Cattail/ Bulrush	3	----	47(30)	18(5)
		6.1	15(6)	104(7)	11(4)
		10.7	----	35(28)	18(7)
	Phragmites	3	----	32(28)	7(4)
		6.1	2(1)	119(11)	4(2)
		10.7	----	35(31)	5(3)
	Canary Grass	3	----	154(147)	27(17)
		6.1	19(12)	584(35)	22(13)
		10.7	----	206(12)	27(16)

developed (as described in the Material and Methods section [Chapter VI, Section A.3.6]) under the bench scale laboratory model of tests. Eight experiments were conducted from January to July, 1981 with synthetic waste water and five experiments were conducted with the domestic sewage in New Hampshire. The synthetic wastewater was tested with phragmites, reed canary grass, bulrush, soft rush, bristly sedge, and several other species; and a control with no plants was run with all bench scale tests. The control consisted of an empty unit which was exposed to sunlight. In most of the experiments the wastewater was recycled continuously, and evapotranspiration was compensated for with distilled water. In several instances with both sewage and the synthetic wastewater the units were tested on a one-pass, or once-through basis to obtain removal rate information that would be similar to the one pass systems tested at the pilot scale. These were referred to as the varied flow experiments where a range of hydraulic rates were tested simultaneously.

The relationship between the hydraulic application rate and the resulting hydraulic retention time in the varied flow experiments as measured by tracer studies are shown in Figure 7.45. Although these reactors were smaller, the hydraulic retention times were similar to the larger units. A comparison of the hydraulic volume of each unit to the flow rate is shown in Figure 7.46 indicating the dependence of the equivalent depth of liquid in the systems at increasing flow rates. The water quality data from the units were quite erratic since mature canary grass was taken from the operating units tested. In these small units the entrapped mass was disturbed, and suspended solids data were of limited value. The COD removal rates in the first varied flow test ranged from 15 grams per m^2/day up to a maximum of 104 grams per m^2/day at an equivalent area loading of 147 cm per day with a hydraulic retention time of 58 minutes as measured at the beginning of the experiment. This changed to 28.9 minutes after six days of use. In most cases the total suspended solids concentration in synthetic wastewater increased in the effluent thereby indicating production of solids in these units.

The influent phosphorus concentration varied from 15 to 21 mg/ℓ, and the resulting uptake was not sufficiently accurate to define removal kinetics with a one pass small scale system. The pH was 7.5 throughout most of the runs in the first varied flow experiment. A relationship similar to phosphorus was also observed with the influence of nitrogen in the single pass systems. A comparison of the total COD removals achieved is given in Figure 7.47 comparing the influent COD at between 200 and 360 mg/ℓ to the effluent achieved over a period of days with reed canary grass at a loading rate of 20 cm/day. This information was developed in the first varied flow experiment in June, 1981, and similar information is comparable in the second synthetic wastewater experiment conducted in July, 1981.

The average BOD concentrations are shown for synthetic wastewater in Figure 7.48, which compares the control unit to the effluent achieved at loading rates of 18, 38 and 74 cm per day. The decreasing efficiency of the process is apparent in this comparison.

C.8. Experiments with recirculating Bench Scale Models

Recirculating batch experiments were conducted with all pollutant parameters in several species to try to obtain an estimate of the removal kinetics and the removal efficiencies that could be obtained after extended exposure in the system. Although a great deal of data was obtained with these experiments there are many questions that remain in relation to the validity of the small scale tests. Example information comparing several variables from these experiments are included in the following section.

Evapotranspiration data from the bench scale experiments showed the significant influence of plant-water uptake over the control. Only the recirculating water was examined. Figure 7.49 compares a control in the winter where the greenhouse temperature was approximately 15°C to the summer control and the evapotranspiration measured with napier grass in summer. It is surprising to note a large increase in evapotranspiration over the controls, since literature values indicate that the water evaporation from water surfaces is

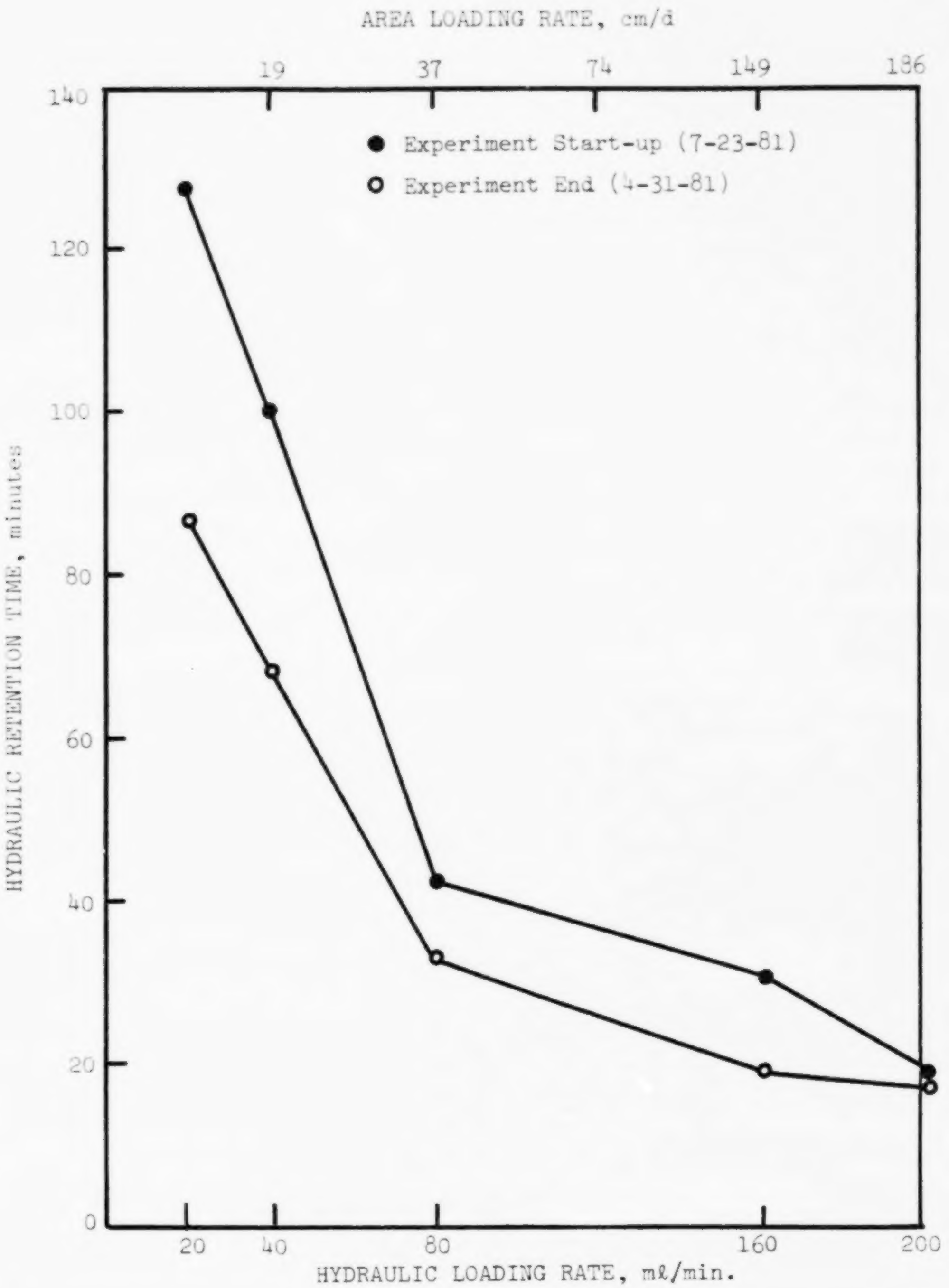


Figure 7.45. Hydraulic retention times in the bench scale varied flow experiment using synthetic wastewater.

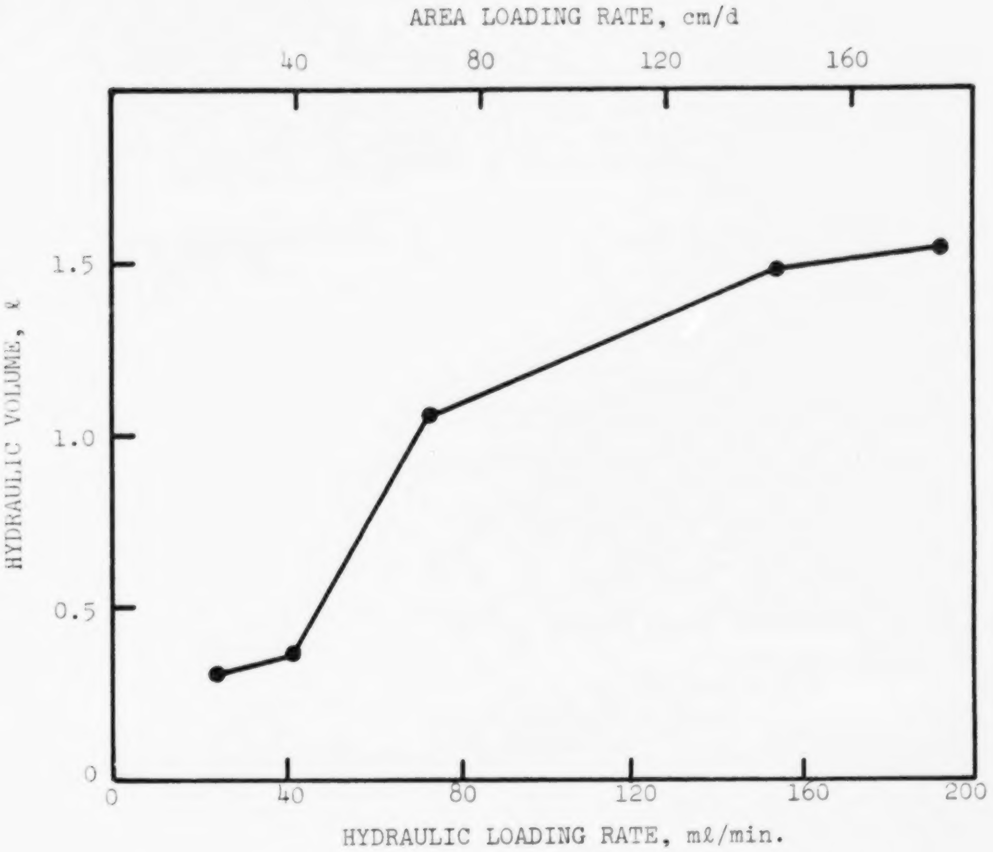


Figure 7.46. Hydraulic volume contained in bench scale varied flow units at different loading rates of domestic sewage.

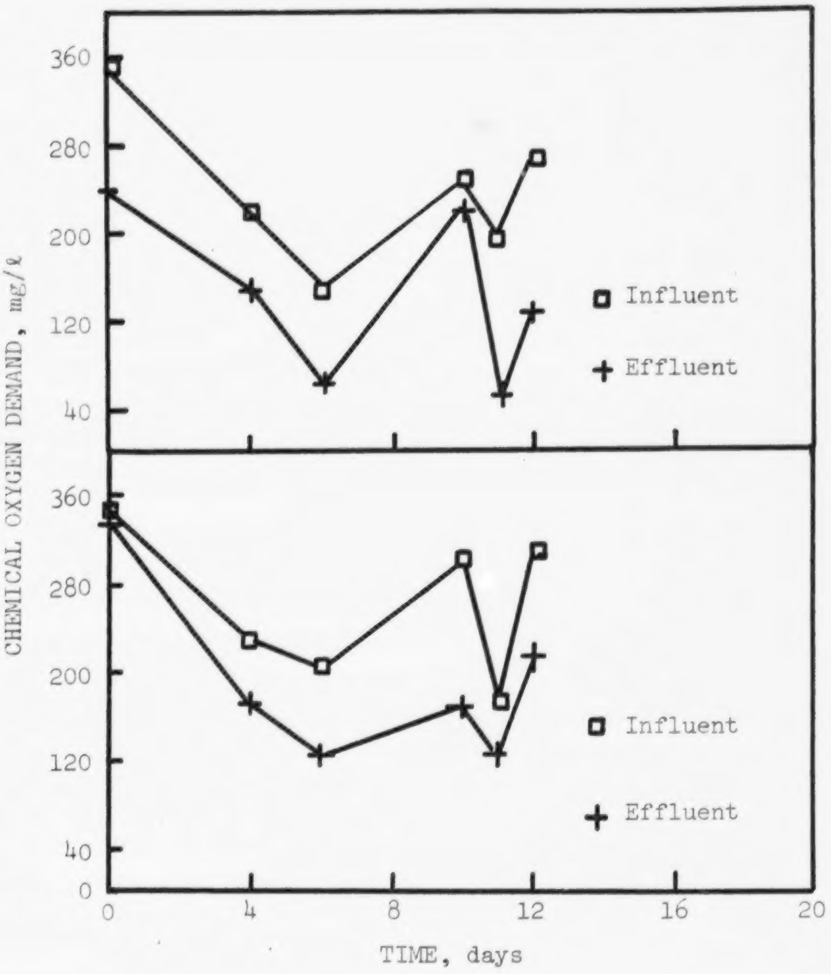


Figure 7.47. Total and soluble COD concentrations of the influent and effluent synthetic wastewater to a reed canary grass bench scale unit loaded at 20 cm/d. First day of analysis was June 12, 1981.

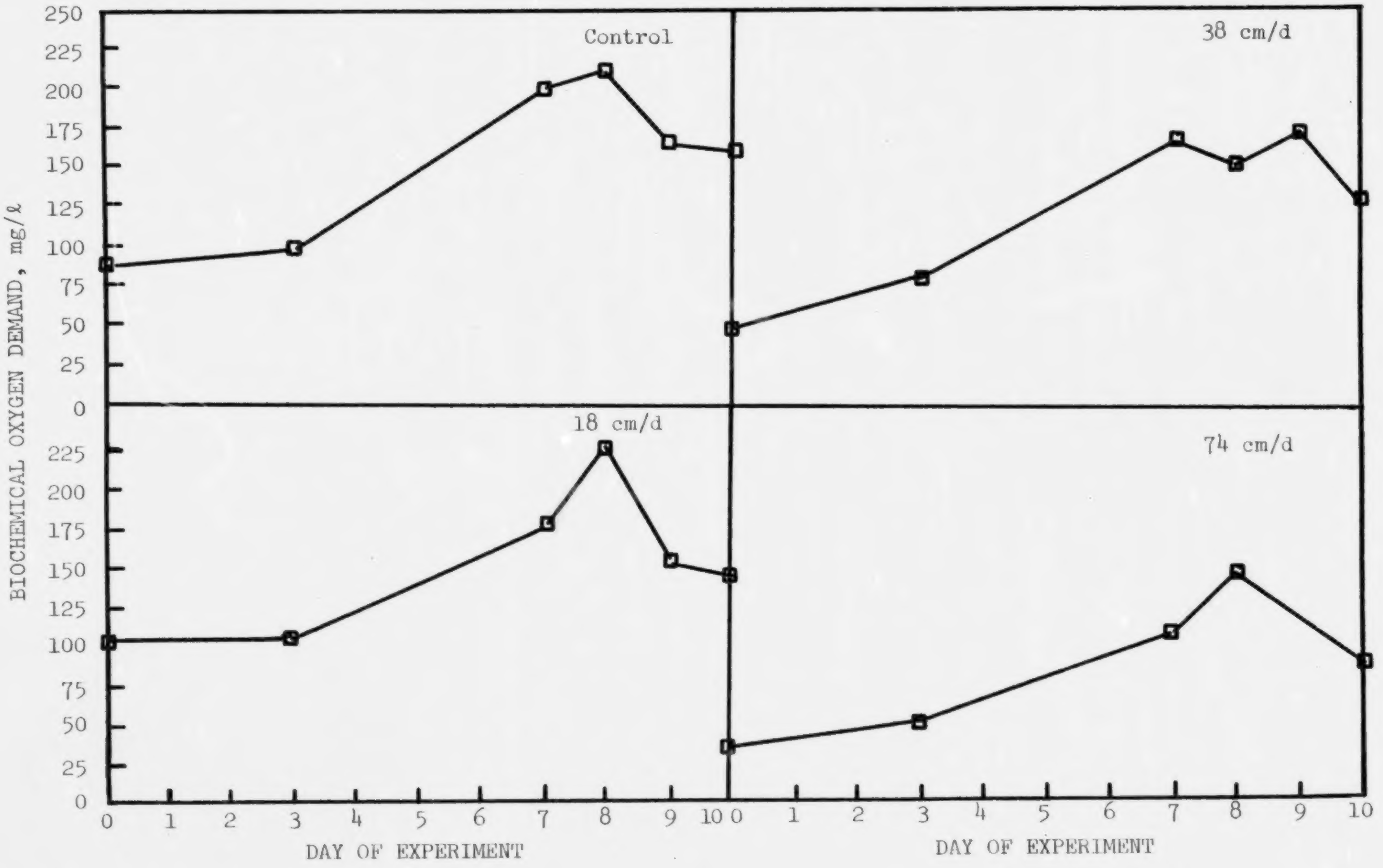


Figure 7.48. Effluent biochemical oxygen demand concentrations of different units in the varied flow experiment, which began July 20, 1981.

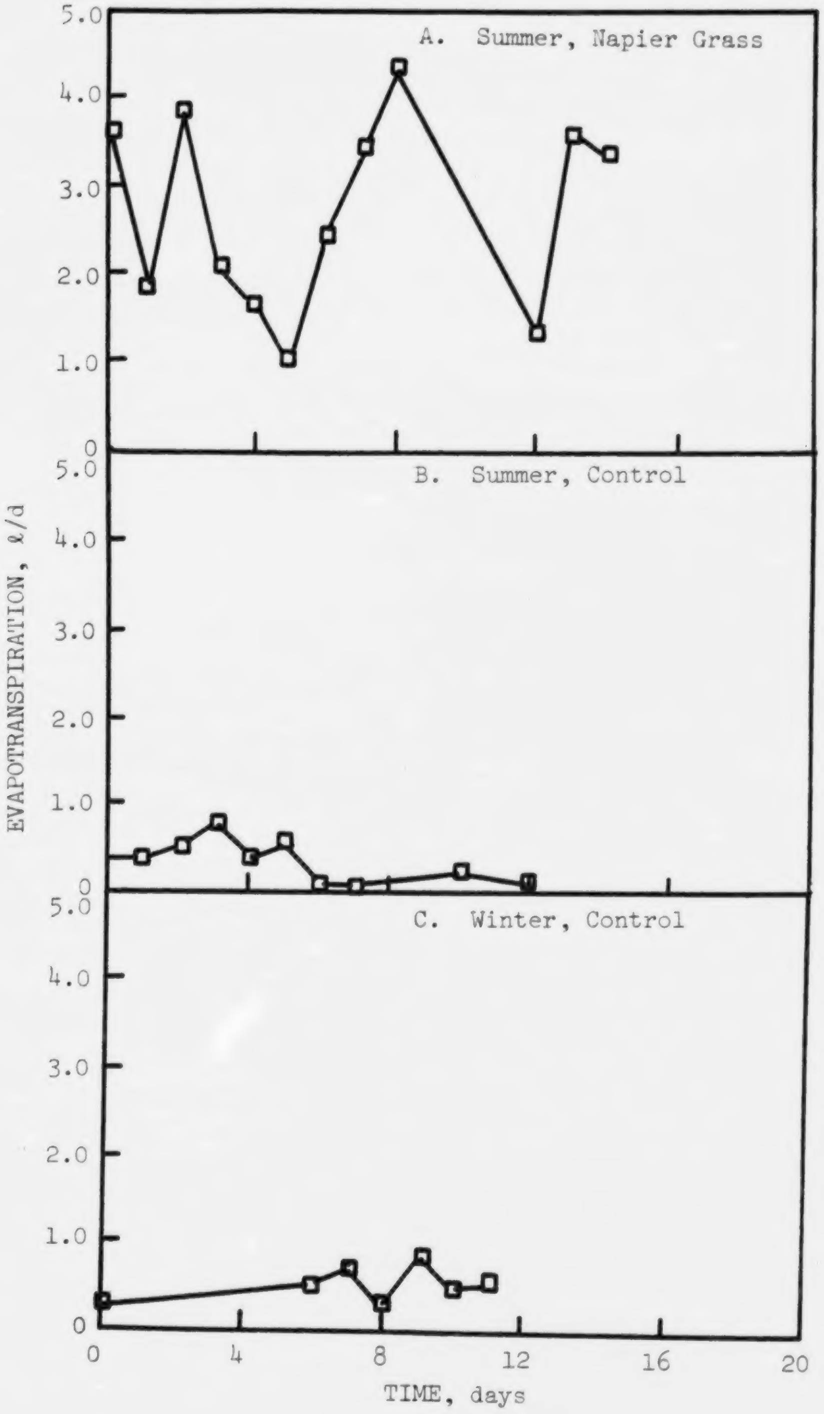


Figure 7.49. Comparison of evapotranspiration from bench scale units. A and B show the effect of a high transpiring plant (napier grass); B and C show little effect from season in empty units.

approximately the same as from healthy plant evapotranspiration. This is perhaps an influence of the large increase in water surface area provided by the extensive capillary action in the nutrient film root system. Evapotranspiration rates for the small scale experiments ranged from $1.2\ell/m^2$ for lake sedge in February to $17.4\ell/m^2$-d for cattails in April.

Uptake of phosphorus by napier grass at the lower temperature and growth conditions shown in Figure 7.50 are compared to the higher uptakes in warmer temperatures in Figure 7.51. Background phosphorus control concentrations ranged from 12 to 15 mg/ℓ. Six mg/ℓ were taken up by the napier grass over a period of eight days to a solution level of about 6 mg/ℓ in cold temperatures. Higher uptake took place in warmer temperatures and phosphorus concentrations decreased in the napier grass unit to close to zero in a smaller period of time under the higher growth rate conditions. It should be noted that the uptake in the control may have been a result of the attached microalgae growing in the control unit.

The results for the nitrogen uptake experiments were less clear perhaps due to nitrogen loss through other mechanisms. In several of the experiments the pH approached 8, thus encouraging the loss of nitrogen through volatilization of ammonia. Example of nitrogen uptake is shown in the nitrogen loss in the control. This is contrasted to the nitrogen uptake in phragmites in January, 1981.

In some cases the nitrogen uptake in these tests indicated a rapid uptake upon initial contact with the growing plant system. Figure 7.52 compares the control for experiments conducted in March of 1981, with initial nitrogen concentration of approximately 50 mg/ℓ, and immediate uptakes (within the first 24 hours) of 20 to 25 mg/ℓ as shown for phragmites, bulrushes and cattails. It would appear in many cases when the plants were healthy the nutrient concentrations could be reduced to values approaching zero. The long-term impact on plants of intermittently increasing the strength of the solution (or wastewater), however, is not known. Growth characteristics under intermittent loadings at these low nutrient concentrations are also unknown.

In these experiments cadmium was also difficult to follow because the removal rates were rapid, with effluents of approximately 0.02 resulting from an influent concentration of 0.2 to 0.3 mg/ℓ. The results, however, were highly variable, and the microalgal film that grew in the controls was also effective in removing the cadmium from some of these experiments.

C.9. Domestic Sewage, Bench Scale Test

Experiments with domestic sewage, similar to those recorded above, were conducted in bench scale units in the Hanover, New Hampshire, greenhouse. A varied flow experiment with applications ranging from 20 to 187 cm/day resulted in the removal rates shown in Figure 7.53. This indicates that there appears to be an optimum area loading rate for both BOD and total suspended solids which occurs above 50 cm/day. The interpretation of this data indicates that the removal rate is substrate limited up to the 100 cm/day loading. Above a certain maximum application rate the pollutant

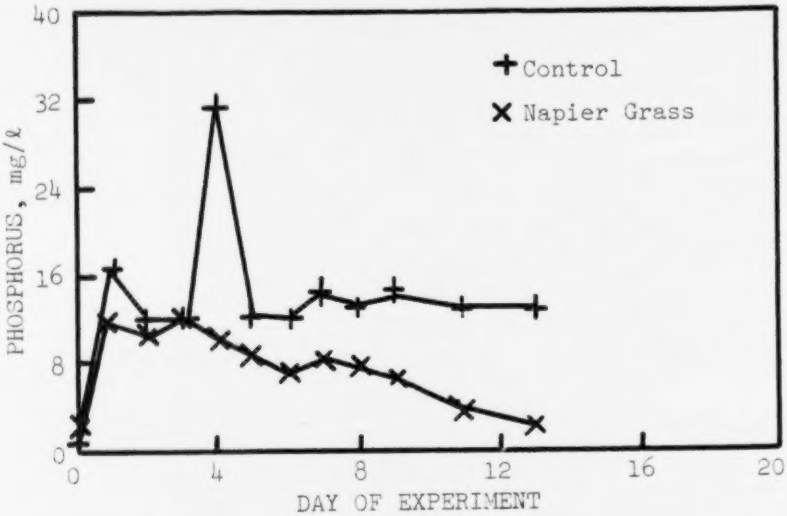


Figure 7.50. Effluent phosphorus concentrations from the control and napier grass units in an early bench scale experiment using a recirculating solution. The experiment began on February 27, 1981.

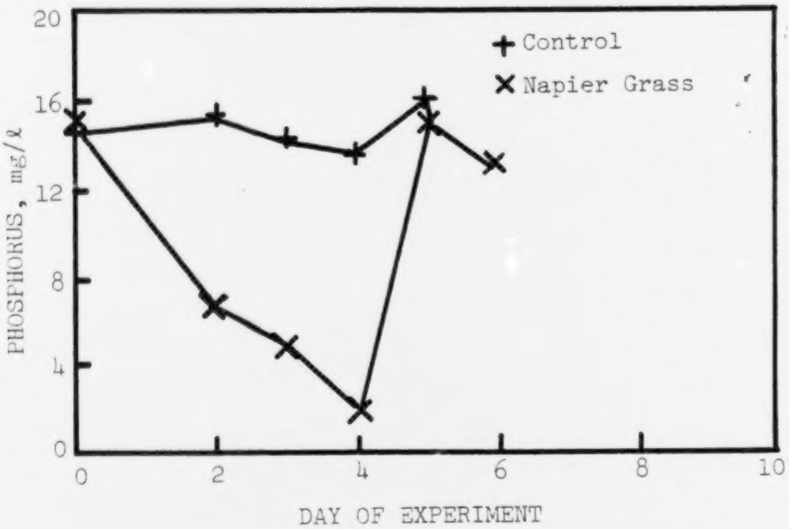


Figure 7.51. Effluent phosphorus concentrations from the control and napier grass units in a later bench scale experiment using a recirculating solution. The experiment began on April 8, 1981.

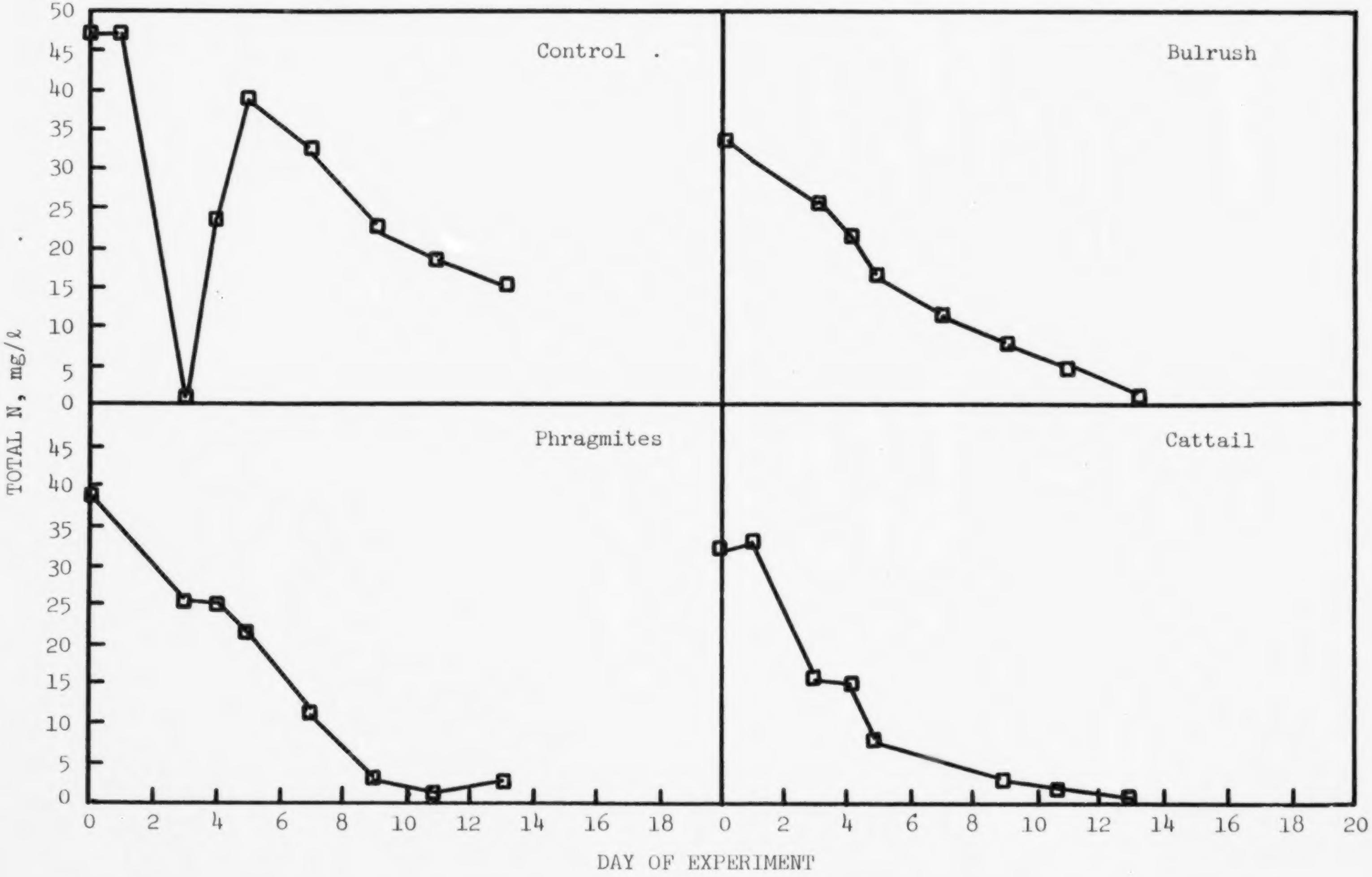


Figure 7.52. Effluent total nitrogen concentrations of synthetic sewage from bench scale units containing several plant species. This series of experiments began March 18, 1981.

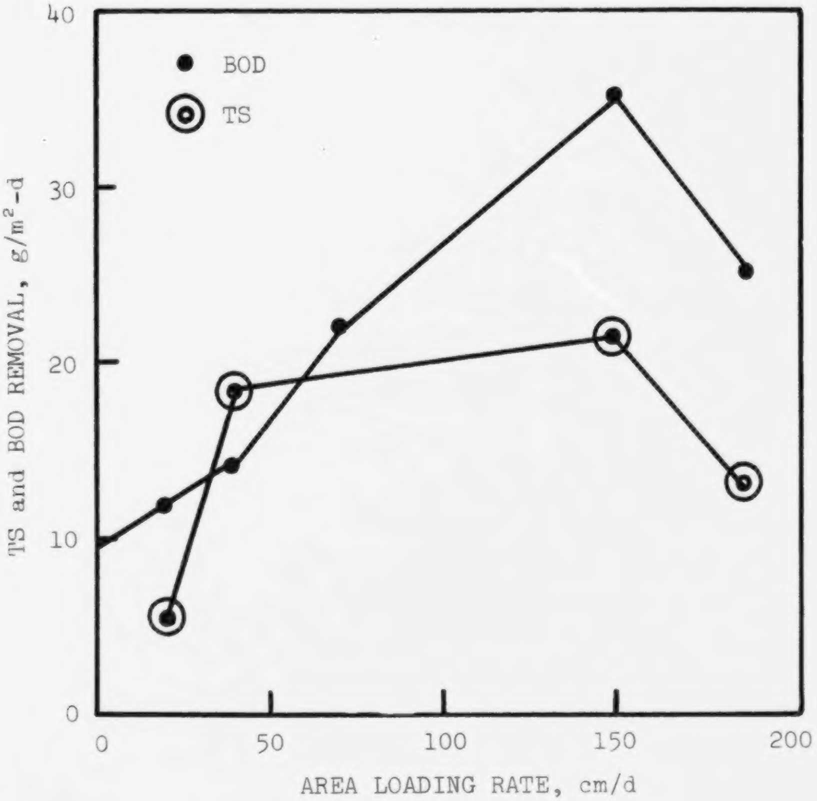


Figure 7.53. Relationship between area loading rate and removal of solids and BOD in bench scale NFT systems using synthetic sewage.

(organic matter or the suspended solids) moves through the system so rapidly that there is little potential for the removal mechanisms to operate efficiently. The generation of more data in small scale experiments such as this would be useful to support this optimization of SS and BOD removals.

A comparison of BOD concentrations in the control unit and those of application rates of 20, 148, 187 cm/day is illustrated in Figure 7.54. This shows that rapid, efficient BOD removal is difficult to achieve at high loading rates.

Due to the rapid growth of the microalgae film in the sewage substrate, particularly in the control unit, the results achieved with the small-scale experiments were of limited value. An example of the effluent BOD concentration in the control as compared to those achieved in several other species units is shown in Figure 7.55. Over 200 mg/ℓ of BOD were removed in less than 24 hours from the 7.5ℓ reservoirs, and the residual BOD of less than 20 mg/ℓ was obtained in all units including the control after four days or less.

C.10. Testing of Optimized Design

Examination of the data midway through the testing program clearly indicated that the pollutants such as BOD and suspended solids were removed by mechanisms much different than the nutrient removal mechanisms. Changing the loading rates and methods of application was one obvious way of optimizing the NFT treatment system. It was felt that if the wastewater could be added rapidly, a quiescent laminar condition would be created, and then unloading could be achieved with a slow laminar flow, suspended solids removal would be maximized and BOD removal might be enhanced. Therefore, a new experimental setup was designed and tested on domestic sewage in a community nearby Cornell University. This unit consisted of three separate species as described in the Materials and Methods chapter.

The batch-wise addition-removal of domestic sewage (as described in the Materials and Methods section) experiments modification used at the Cayuga Heights sewage treatment plant were conducted between August, 1981 and October, 1981. These experiments were highly successful, albeit limited in scope due to the time required to acclimate the systems and due to adverse weather in early winter. Note that these were the only experiments where raw unsettled sewage was used as the feed. Steady state condition information for the two loading rates tested, 20 cm/d and 30 cm/d, are given in Table 7.6. The treatment efficiencies for organics and suspended solids were surprisingly good. Effluent suspended solids were always less than 29 mg/ℓ, and often less than 15 mg/ℓ at the higher loading rate. Total COD reductions averaged nearly 80 percent.

The improvement in effluent quality between the 20 cm/d and 30 cm/d tests is most likely related to system acclimation and microbial mass accumulations. Samples for the latter loading condition were taken after the system had matured for several weeks of operation at the higher loading rate. Settleable solids in the effluent, measured in the Imhoff settling cone, were consistently negligible compared to the suspended solids.

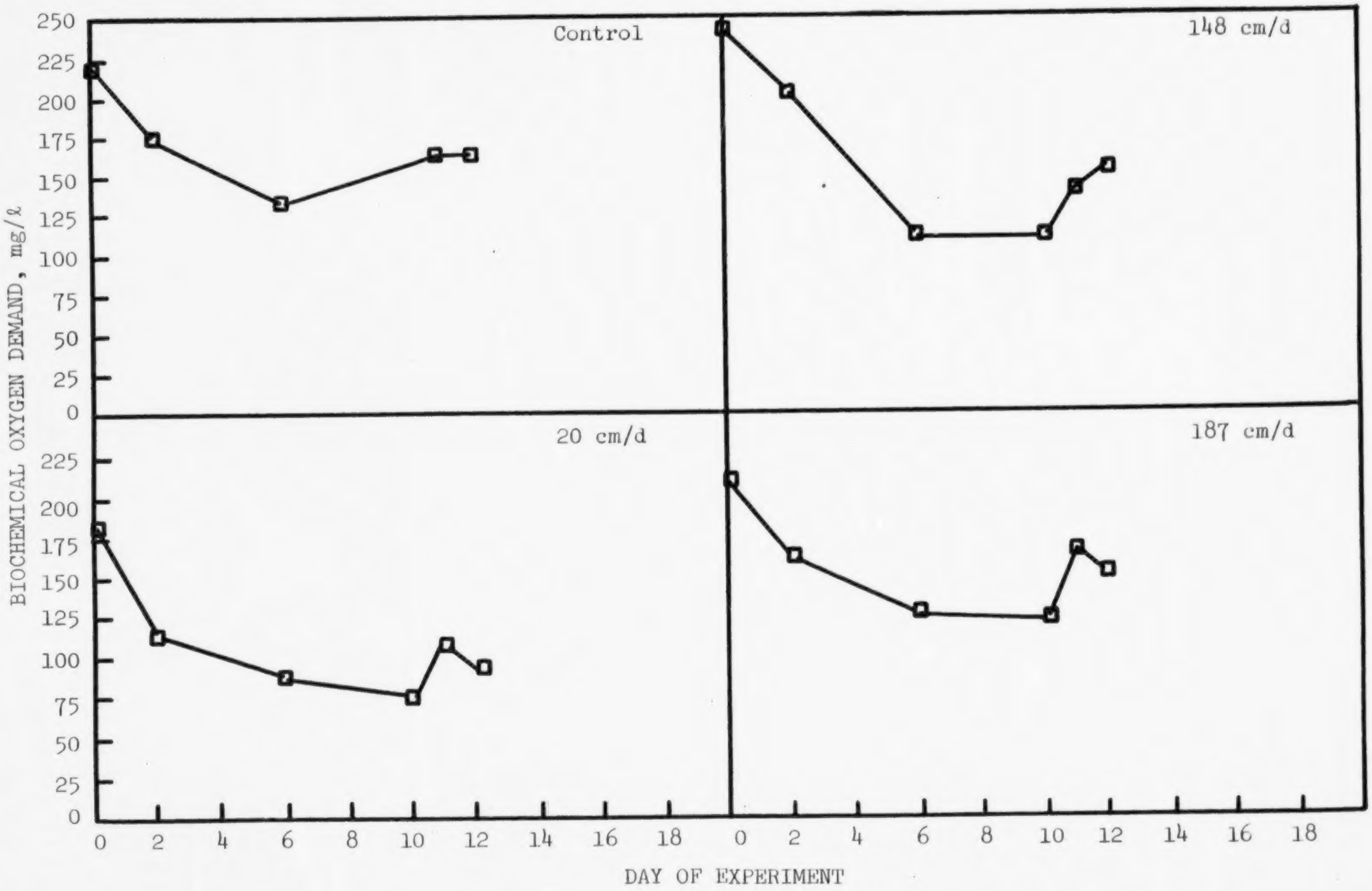


Figure 7.54. Effluent biochemical oxygen demand concentrations of units at different loading rates in the varied flow experiment using domestic sewage. The experiment started on June 22, 1981.

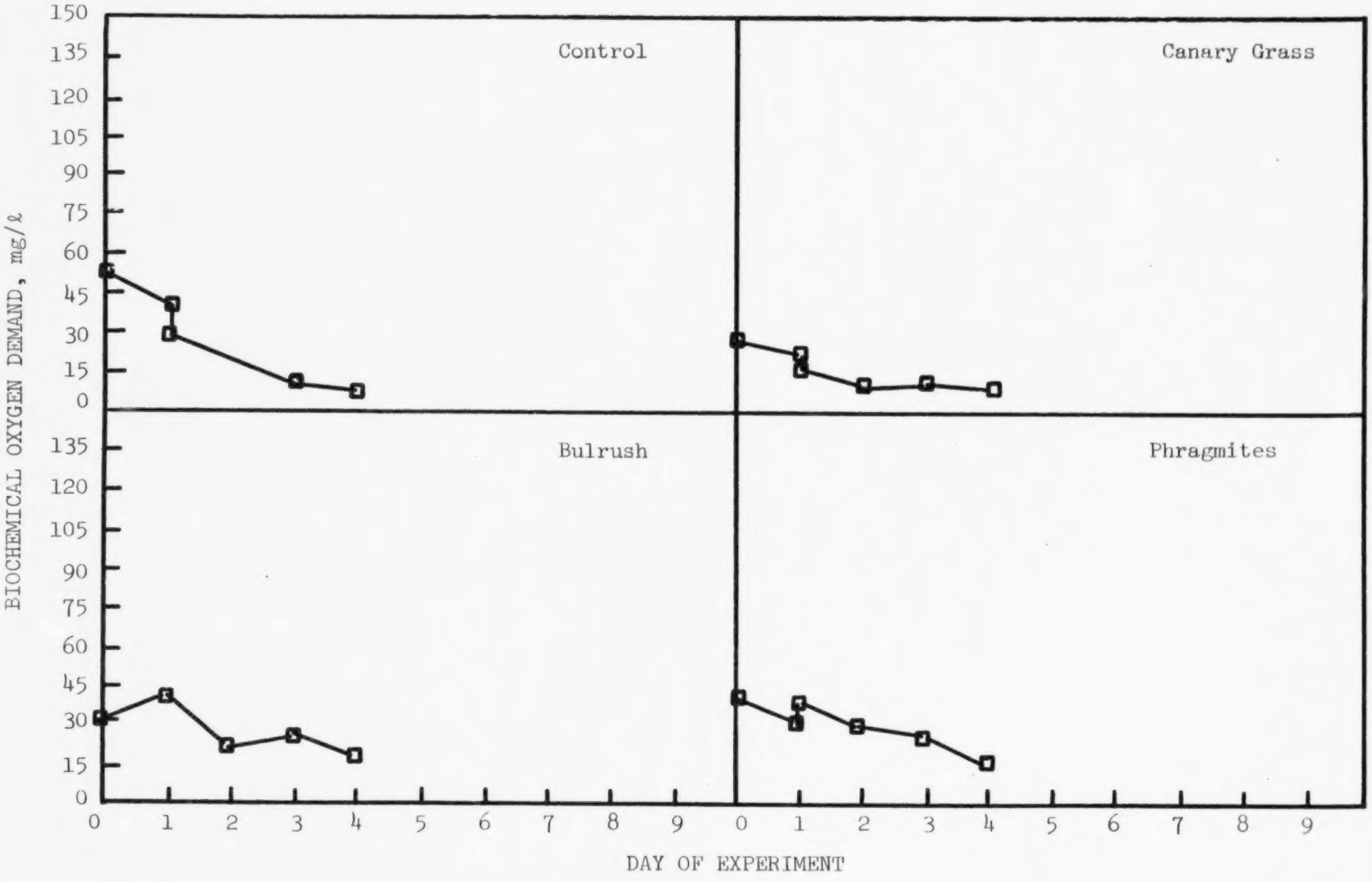


Figure 7.55. Biochemical oxygen demand concentrations over time in recirculating domestic sewage units containing different plant species.

TABLE 7.6. SUMMARY OF OPTIMIZED OPERATION OF THE NFT AS A PRIMARY AND SECONDARY COMBINED TREATMENT SYSTEM USING INTERMITTENTLY LOADED AND UNLOADED PLANTS. EXPERIMENTS WERE CONDUCTED AT THE CAYUGA HEIGHTS VILLAGE TREATMENT FACILITY.

Area Loading Rate cm/day	Parameter	Number of Samples	Influent Quality			Effluent Quality		
			Mean	High	Low mg/ℓ[1]	Mean	High	Low
20	Soluble COD	12	88	124	71	83	93	62
	Total COD	12	283	358	168	116	148	93
	Suspended Solids	4	125	226	68	43	105	15
	Total Solids	1	680	680	680	590	590	590
	Settleable Solids	4	7.8	14.2	2.1	<0.1	<0.1	<0.1
	NH_4^+-N	6	29	32	27	7	13	<1
	Organic-N	6	12	16	8	4	10	<1
	TKN	6	41	48	35	11	15	5
30	Soluble COD	14	107	176	45	44	59	30
	Total COD	12	317	542	193	72	92	33
	Suspended Solids	9	139	299	71	15	29	5
	Total Solids	5	610	690	570	540	570	500
	Settleable Solids	7	4.0	12.0	0.7	<0.1	<0.1	<0.1
	NH_4-N	4	31	32	29	12	12	11
	Organic N	2	9	11	6	5	5	5
	TKN	2	40	43	35	17	17	16

[1] All units are mg/ℓ except those for settleable solids, which are ml/1000 ml.

Based on the limited data, typical results indicated complete removal of settleable solids, total COD conversions of approximately 75-80%, soluble COD conversions averaging around 60%, and suspended solids removals on the order of 90%. Further testing of this optimized treatment sequence with raw sewage is strongly recommended.

Total nitrogen removals of 75 percent at a 20 cm/d loading rate, and nearly 60 percent at 30 cm/d, could be significant if the results could be duplicated in larger scale tests.

As noted earlier, questions remain as to the effect of pumping on the solids in the system. Relatively little data collection was accomplished before the experiment terminated. There was also significant scatter in individual data points, so questions of reliability cannot be addressed based on this work. To be a viable option, the system would also have to be tested at loading rates higher than 30 cm/day to insure that area requirements could be minimized.

In reviewing the three purposes of this experiment, three results are apparent. First, although testing was only accomplished at a moderate flow rate, the system did perform well in solids capture and conversion of organic solids. Second, it was established that the plants tested could cope well with the conditions imposed upon them. Napier grass performed unexpectedly well; bulrush flourished as expected under alternate flooding and drainage; cattail maintained itself but did not grow as well as the other plants, possibly due to fluctuating water level and reducing conditions. The most significant observation in this area was the performance of the napier grass, which promises excellent opportunities for taking advantage of capabilities to filter solids and convert nutrients. Third, this system appears to have potential as a pretreatment unit due to solids treatment capability demonstrated in the study.

Taking the average suspended solids values from Table 7.5 and daily volumetric wastewater loading from Table 7.4, the conversion efficiency for suspended solids is computed as 38.4 gm SS treated/m^2-day at 30 cm/day. This compares favorably with 16.4 gm SS treated/m^2-day at 20 cm/day, the highest loading rate tested with sewage in New Hampshire. COD conversion and nitrogen uptake data also point to the possible refinement of this technique to replace some conventional primary and secondary treatment processes, but much more data are needed to confirm system reliability. Heavier loadings must also be treated in order to achieve an optimized process design.

D. WATER BALANCE AND ENERGY TRANSFER

This section contains empirical data on water losses in an NFT system and a theoretical analysis of the potential for losses and the possibility for water recovery.

Evapotranspiration data from a pilot scale control unit at Cornell are summarized in Table 7.7 for the pilot scale units for applications to reed canary grass. Mean monthly evapotranspiration in the 9.3 m^2 size pilot units ranged from 2 to 6 ℓ/m^2/day and had maximum values approaching 125,000 ℓ/ha/day. Table 7.8 compares the losses in a 9.3 m^2 pilot unit containing reed canary grass to those measured in the recirculation tests (bench scale units) with synthetic wastewater. This information illustrates the effects of the plant NFT system on ET as compared to an open water control where the flow rates were exactly the same and also contrasts the larger NFT units to the smaller units. Several interesting comparisons can be made with this information. The smaller units appeared to have significantly higher water losses than the larger pilot scale units. The water losses from the control were often around one tenth of that lost from the small scale unit with mature plant systems. The differences between the large scale unit and the bench scale units may reflect the uninhibited movement of air around the water surface and plants. The difference between the control unit and the NFT unit is more difficult to explain. The significant increase in ET from the NFT units with plants over a control unit suggests that the increased surface area available for water evaporation in the leaf surface can increase water losses. During the warmer periods of the year, reed canary grass had losses approaching 150,000 ℓ/ha-day, values that appear to be higher than those reported by others.

TABLE 7.7. EVAPOTRANSPIRATION OF THE 9.3 m^2 REED CANARY GRASS UNIT OF THE CORNELL BRACEHOUSE. DATA WERE COLLECTED DURING THE TESTING OF THE 27.9 m^2 MULTISPECIES SYSTEM IN THE SAME GREENHOUSE IN 1981.

Dates		Average Evapotranspiration ℓ/ha-d	Standard Deviation ℓ/ha-d	Number of Observations
From	To			
2-19	2-28	21500	9500	12
3-1	3-31	24700	9600	30
4-1	4-30	39100	23300	28
5-1	5-31	58100	26900	25
6-1	6-30	45900	21300	28
7-1	7-31	56900	22300	31
8-1	8-16	56100	26100	15

This trend was also observed for the domestic sewage data, as shown in Table 7.9. Average losses of water from the sewage systems approached 100,000 ℓ/ha-day, and the difference between the controls and the various plants was also significant, ranging from double to ten times the control amount. Losses in these small units, however, did not approach the high values achieved with the Cornell test units.

Although this information appears to be encouraging in terms of recovery of high quality water in the form of evapotranspiration, it should be kept in mind that the ET losses represent huge energy conversions. For example, the loss of 15,000 ℓ/ha-day, if recovered, and requiring an energy investment, would cost approximately $400/ha-day. Reasons for this are discussed in the following energy balance and water balance sections.

A design project was undertaken to evaluate the feasibility of recovering water and energy from ET. This section presents a short overview of the quantities of water vapor which are lost from NFT plant systems. Two recovery systems which were designed for conditions in Ithaca, New York, are evaluated; and the technical and economic feasibility of these two recovery systems are discussed. The material is presented in more detail in another report (Pompe, 1983).

D.1. ET Rates

Results of experiments measuring ET rates from the NFT wastewater treatment systems were available only at the conclusion of the design project. Therefore ET rates were predicted based on a model developed for greenhouse conditions by Lake et al. (1966):

$$ETP = 0.38\, R_n' + 0.17(\ell_a - \ell_d) - 0.17 \qquad (7.1)$$

TABLE 7.8. COMPARISON OF EVAPOTRANSPIRATION BETWEEN A CANARY GRASS PILOT SCALE UNIT AND BENCH SCALE UNITS CONTAINING DIFFERENT PLANT SPECIES AT CORNELL USING NUTRIENT SOLUTION OR SYNTHETIC SEWAGE. ALL ET MEASUREMENTS ARE REPORTED AS $\ell/ha^{-}d$. ALL EXPERIMENTS WERE IN 1981.

Dates		Pilot Unit ET	Bench Scale ET					
			Unit					
From	To	Average Std. Dev. N	1	2	3	4 Average Std. Dev. N Species	5	6
2-27	3-12	22500	11600	46500	48400	101000	102000	86500
		4500	9000	12900	12300	31600	21300	26500
		14	14	12	12	12	12	12
			Control	Millet	Lake Sedge	Canary Grass	Soft Rush	Napier Grass
3-18	4-2	30100	19400	65200	49700	115000	69700	84500
		13400	20000	24500	19400	51600	29700	20600
		15	16	16	16	12	16	16
			Control	Cucumber	Phragmites	Canary Grass	Bulrush	Cattail
4-8	4-23	38800	20600	87700	67100	142000	76100	174000
		22600	14800	31600	42600	56100	63900	72300
		16	11	12	12	12	15	12
			Control	Millet	Rose	Canary Grass	Phragmites	Napier Grass
4-28	5-11	45900	45200	98100	111000	38700	36100	63200
		24600	30300	32300	33500	36100	9000	30300
		11	13	13	13	13	13	13
			Control	Cucumber	Canary Grass	Bulrush	Cattail	Phragmites
5-14	5-21	55600	31000	43900	42600	50300	43900	42600
		21200	19400	4500	23900	27100	18100	13500
		6	6	6	6	6	6	6
			Control[1]	120 MEQ/ℓ	60 MEQ/ℓ	30 MEQ/ℓ	15 MEQ/ℓ	0 MEQ/ℓ

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[1] This experiment tested salt concentrations; unit 1 was empty, while units 2 through 6 contained canary grass.

TABLE 7.9. COMPARISON OF EVAPOTRANSPIRATION BETWEEN A 27.9 m^2 PILOT SCALE SYSTEM AND BENCH SCALE UNITS CONTAINING DIFFERENT PLANT SPECIES USING DOMESTIC SEWAGE. ALL ET MEASUREMENTS ARE REPORTED AS $\ell/ha^{-}d$. ALL EXPERIMENTS WERE IN 1981.

Dates		Pilot System ET	Bench Scale ET					
			Unit					
From	To	Average Std. Dev. N	1	2	3	4 Average Std. Dev. N Species	5	6
3-23	4-5	83500	14800	78700	98100	32300	30300	51600
		127000	21300	61300	56800	15500	31600	36800
		4	13	13	12	12	13	13
			Control	Cucumber	Canary Grass	Phragmites	Bulrush	Cattail
4-17	4-30	96800	29000	54200	84500	27700	66500	44500
		49800	38700	32900	41900	20600	56100	40600
		11	13	13	13	11	13	11
			Control	Rose	Canary Grass	Phragmites	Bulrush	Cattail
5-8	5-21	93200	7100	26500	54200	43900	49000	95400
		34100	11600	19400	39400	36800	43200	73500
		14	12	13	13	13	13	13
			Control	Bulrush	Canary Grass	Phragmites	Cattail	Napier Grass
5-22	6-4	107000	32300	60000	80000	34200	66500	71000
		0	16100	24500	31600	16100	41900	22600
		1	13	13	13	12	7	11
			Control	Tomato	Canary Grass	Bulrush	Phragmites	Cattail

where ETP = potential evapotranspiration,[1] mm H_2O/day

R_n' = net solar radiation inside the greenhouse, mm H_2O/day[2]

ℓ_a = saturation vapor pressure, mm Hg

ℓ_d = actual vapor pressure at the outside air at 0900 hr, mm Hg

The design of the recovery systems was based on potential ET rates. Actual rates were assumed to be close to potential rates.

ETP rates are a function of solar radiation and were predicted for January and July conditions to be 4,100 and 26,200 ℓ/ha-d, respectively. Total yearly ETP losses were computed through integration after assuming a sigmoidal shape for the ET curve over the year (which matches the solar radiation variation). They were calculated to be 5.6×10^6 ℓ/ha-yr.

The actual ET rates which were measured in the NFT wastewater treatment units fluctuated sharply from day to day. Average rates from the large experimental systems ranged from 21,500 to 56,000 ℓ/ha-d for February and July, respectively. The predicted ETP rates were lower than these values, but were in the same order of magnitude. The effect of the higher actual ET rates in the feasibility of the recovery systems is discussed in the later sections.

D.2. ET Recovery Systems

Various approaches can be used to remove water vapor from air. Exposure of the air to a surface which has a temperature lower than the dewpoint temperature of the air is one possibility (ASHRAE, 1981). The technical feasibilities of using an air-to-air heat exchanger and that of using a refrigerative dehumidification system with a compression cycle are evaluated in this section.

The capacity of both systems is a nonlinear function of the size of the greenhouse. The size of the greenhouse needs to be known for the design. The systems were evaluated for a greenhouse with a floor area of 200 m^2, a volume of 890 m^3 and a cover area of 440 m^2. The total amounts of ET water vapor for this size greenhouse were calculated to be 82 and 524 ℓ/day for

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[1] Potential evapotranspiration is defined as the ET from a crop which covers the soil completely and which water supply is not limiting (Decker, 1967).

[2] Solar radiation can be expressed in mm H_2O/day by multiplying the radiant energy by its latent heat equivalent for water. The latent heat of water at 20°C and 1 atmosphere equals 2453 kJ/kg. The evaporating power of 1 MJ/m^2 is then 0.408 mm H_2O.

January and July conditions. They were assumed to be produced during 12 hours per day. The instantaneous ET rates for these months were computed to be 1.9×10^{-3} and 12.1×10^{-3} kg H_2O/sec, respectively.

An energy balance was constructed around the hypothetical 200 m^2 greenhouse. The results for typical January and July days in Ithaca, New York, are shown in Figure 7.56. A net energy loss for the whole greenhouse of 4.4×10^3 MJ/d was computed for January, while in July an excess of 433 MJ/d of energy was calculated.

D.2.a. Necessary cooling capacity

The cooling capacity which is necessary to condense the ET water vapor was computed based on the following two equations (ASHRAE, 1981).

Equation 2 calculates the relationship between the required humidity ratio of air and the mass flow rate of air, while Equation 3 computes the necessary rate of heat transfer:

$$W_2 = W_1 - ET/m_a \qquad (7.2)$$

$$q = m_a\{(h_1 - h_2)-(W_1 - W_2)h_{w2}\} \qquad (7.3)$$

where

W = humidity ratio of air, kg H_2O/kg dry air
ET = amount of evapotranspiration for the whole greenhouse, kg H_2O/sec
M_a = mass flow rate of air, kg/sec
q = rate of heat transfer, kW
h = enthalpy, kJ/kg

and the subscripts are defined as

1 = entering air
2 = exiting air
a = air
w2 = exiting water

The relationship between the condensation temperature and the mass flow rate of air for January and July conditions is shown in Figure 7.57, and this figure also shows the required cooling capacity for mass flow rates at given temperatures. The designs for the two recovery systems were based on this figure. The necessary rate of heat transfer at a given mass flow rate of air would be larger in Figure 7.57 if the measured ET rates were used to construct the figure instead of the lower computed rates.

D.2.b. Air-to-air heat exchanger--

A counterflow air-to-air heat exchanger which uses colder outside air to condense the water vapor from the greenhouse air was evaluated. The configuration is shown in Figure 7.58. Outside air is forced through the inside tube into the greenhouse. The warm greenhouse air is forced between the two tubes and is vented to the outside. The whole system would be built

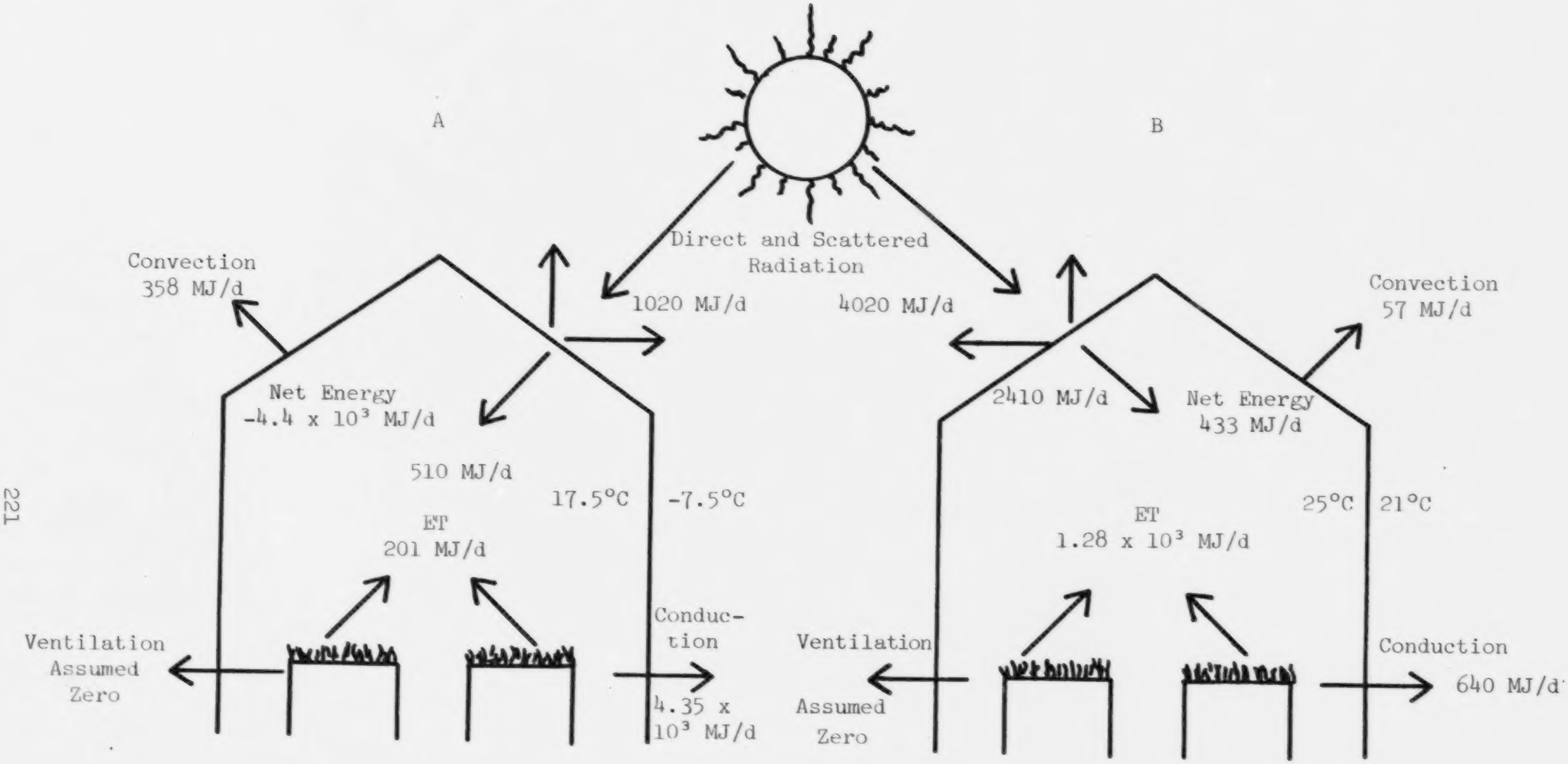

Figure 7.56. Schematic energy balance for a hypothetical greenhouse in January (A) and July (B) in Ithaca, New York. Greenhouse measures 10 x 20 m and is covered by a double layer of polyethylene.

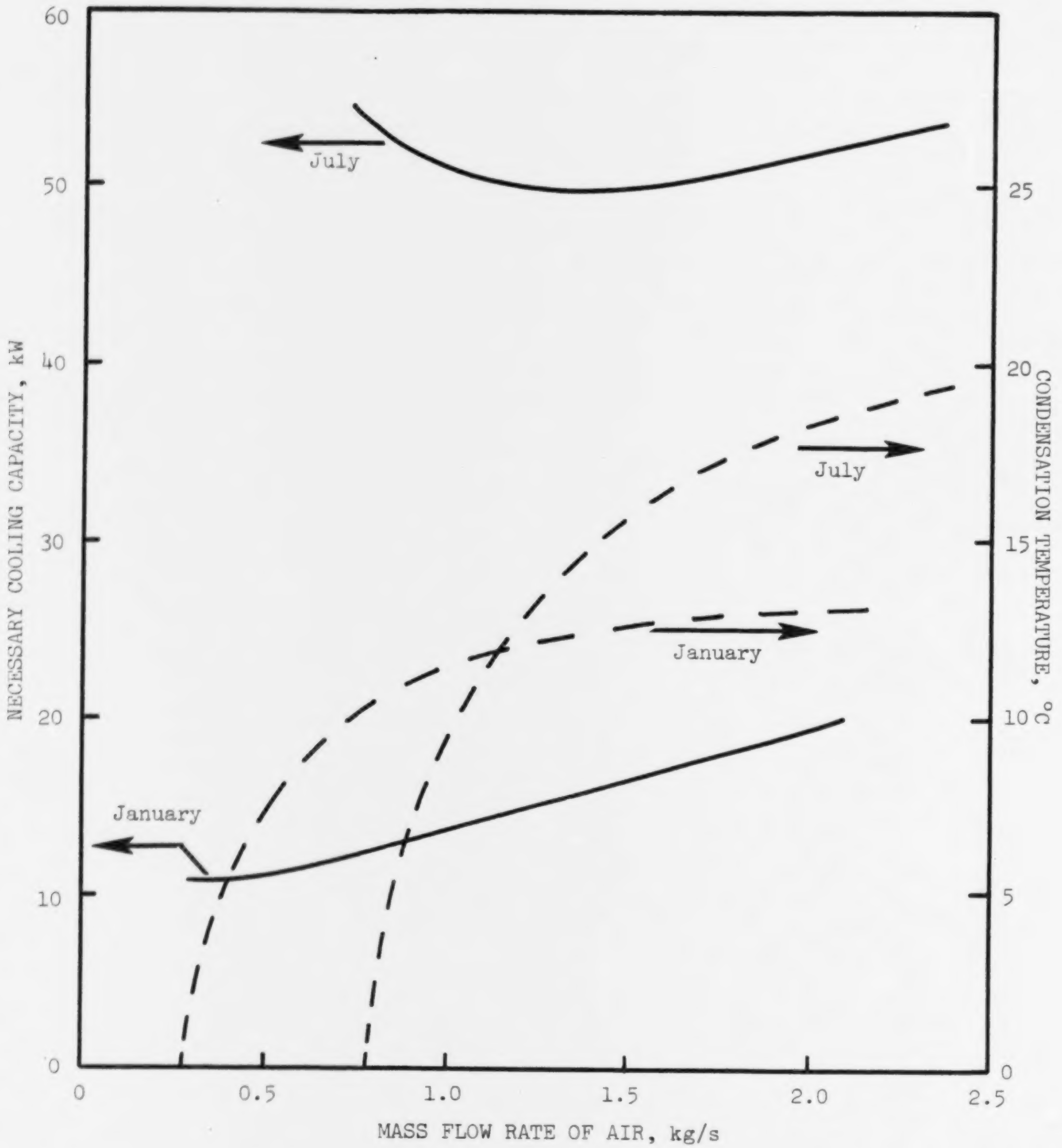

Figure 7.57. Condensation temperature and cooling capacity necessary to recover all ET vapor as a function of mass flow rate of air.

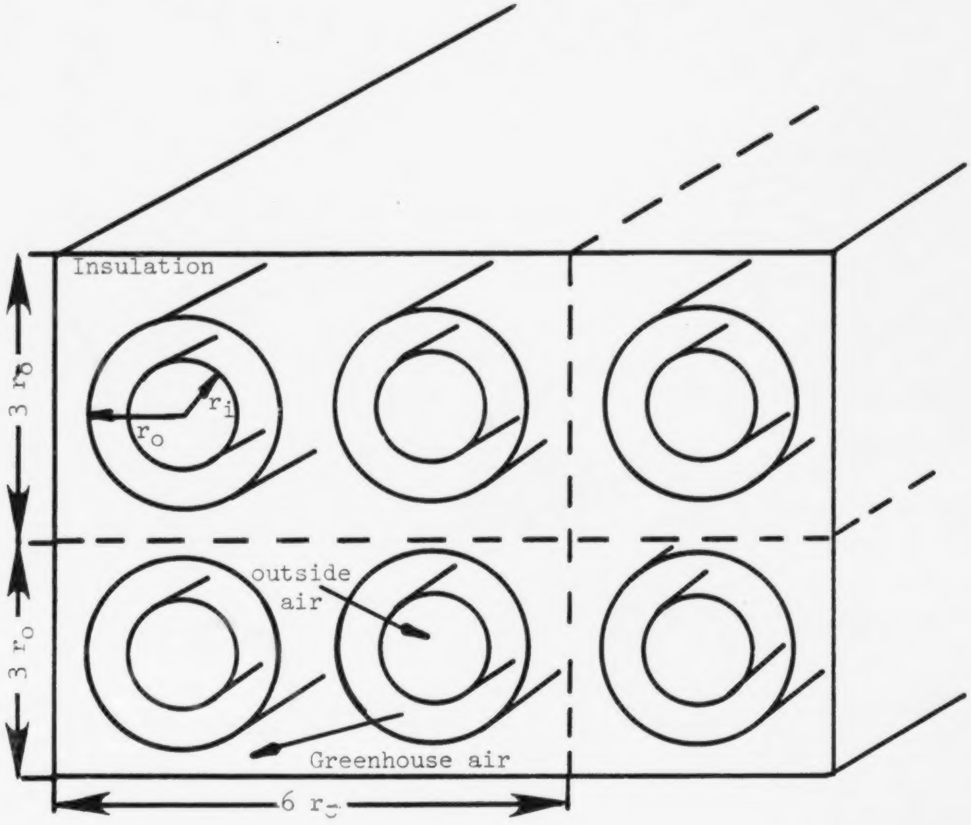

Figure 7.58. Configuration of the air-to-air heat exchanger used in design estimates.

sloped down towards a condensate collection point. The temperature of the outside air would increase in the direction of its flow as a result of the absorption of both sensible and latent heat from the exiting greenhouse air.

Meteorological data were obtained from the Department of Atmospheric Sciences at Cornell University, while greenhouse conditions were gathered through actual measurements. A method which employs the heat exchanger effectiveness approach was used to determine the dimensions of the heat exchanger (ASHRAE, 1981, Kreith and Black 1980). Three variations of the system were evaluated, containing 2, 4 and 6 sets of tubes.

For January the lengths of these heat exchangers which would be necessary to remove all ET vapor were computed to be 196, 143 and 82 m for the systems with 2, 4 and 6 sets of tubes, respectively. These are much longer than the 20 m greenhouse for which they were designed. They were rejected since they were not suited for January conditions. If actual measured ET rates had been used for the design, the system would have been even larger. In July the temperature of the outside air is equal to the dewpoint temperature of the greenhouse air. Therefore no condensation of water vapor will occur in an air-to-air heat exchanger using outside air. This approach was also deemed infeasible for July condensation.

D.2.c. Refrigerative dehumidification--

A refrigerative dehumidification system with a compression cycle was evaluated as an alternative approach for condensation of the water vapor. Such a system consists of four basic components: the compressor, the condenser, an expansion valve, and an evaporator. The energy which is absorbed by the evaporator and that which is added by the compressor is released by the condenser (Althouse *et al.*, 1979).

If all water vapor lost through ET were to be recovered, the cooling capacity of the system needs to be at least 10.7 kW for January and 50.4 kW for July (see Figure 7.57). The temperature of the air at the evaporator would need to be 5°C and 12°C at mass flow rates of air of 0.4 and 1.15 kg/sec for January and July, respectively.

Systems which can provide these capacities are commercially available. This approach was considered to be technically feasible. The evaporator was designed to be inside the greenhouse, while the condensing unit would remain outside. Ducts would connect the two components. The heat which would be released by the condensing unit could be recovered by guiding the cooled greenhouse air (or part of it) through these ducts over the condensing unit and back into the greenhouse. The CO_2 supply necessary for photosynthesis may be depleted in such a closed greenhouse, and artificial CO_2 addition may be necessary.

The daily energy input requirements for this ET recovery system were computed to be 62.4 kWh and 188.0 kWh for the 200 m^2 design greenhouse in January and July, respectively. The system would produce 82 and 524 ℓ daily in these respective months. Some of this energy is lost due to energy conversion inefficiencies, while some energy is recovered from the heat of condensation. A mass and energy balance showed that in January the daily energy input of 62.4 kWh into the 200 m^2 greenhouse would produce 82 ℓ/day of condensate (see Figure 7.59). This would remove 128.4 kWh from the 200 m^2 greenhouse daily, while 159.6 kWh would be released by the condensing unit. If the air were guided over the condensing unit and back into the greenhouse, a net increase of 31.2 kWh of energy would be obtained daily. In July 188.4 kWh of daily energy input to the compressor would produce 524 ℓ/day of condensate while removing 604.8 kWh of heat daily.

D.3. Economic Considerations

In the economic evaluation the net present value of the construction costs and the operation and maintenance costs were taken into account. Only the compression refrigerative system was evaluated since the air-to-air heat exchanger proved to be technically infeasible.

Yearly total costs were calculated to amount to $4,615, while the yearly benefits were estimated at $1,615. The total yearly water recovery from the ET recovery was predicted to be 111 m^3/yr. Water production costs were calculated to be \$27/m^3. Conventional treatment of wastewater to potable standards were reported to be \$0.31/m^3 at the Factory 21 sewage treatment plant in Orange County, California (Argo and Montes, 1979). Water production through ET recovery from NFT wastewater treatment systems would be much more costly and was rejected as economically feasible at this time.

D.4. Alternative Approaches for Condensation

Other media could serve as the coolant in a heat exchanger. Cold water could be used instead of cold air. Water will transfer heat faster than air does as a result of its much higher density. One naturally available source for cold water is the sewage influent itself or groundwater. The wastewater itself may have a low enough temperature to serve as the coolant. Water-to-air heat exchangers may prove to be more feasible than the air-to-air heat exchanger examined here. An evaluation of such a heat exchanger is recommended.

E. NUTRIENT UPTAKE

Tables 7.10 through 7.14 summarize the dates, yields, dry weights of plant harvests and the composition of the material as subsampled from the harvested materials. This information is useful for illustrating the composition of the material as well as the nutrient and heavy metal compositions that may occur in the NFT unit treating wastewater. The control that was fed an inorganic nutrient solution for the duration of the study from 1979 through 1980 is useful for comparing the impact of the synthetic wastewater with cadmium addition to the reed canary grass. The nitrogen composition for this plant for the intensive period studied ranged from a maximum of 5.28 percent nitrogen to a low of 3.62. The high concentrations of nitrogen always occurred during lower productivity periods and low temperature conditions, and the lower nitrogen contents occurred during higher productivity. The phosphorus content ranged from 0.40 to 0.70. Reed canary grass yields were plotted in Figure 7.60 and ranged from 0.36 to 9 g/m^2/day of dry matter. The conversion rates of nutrients were calculated based on the yield data and the elemental concentrations as reported in the tables.

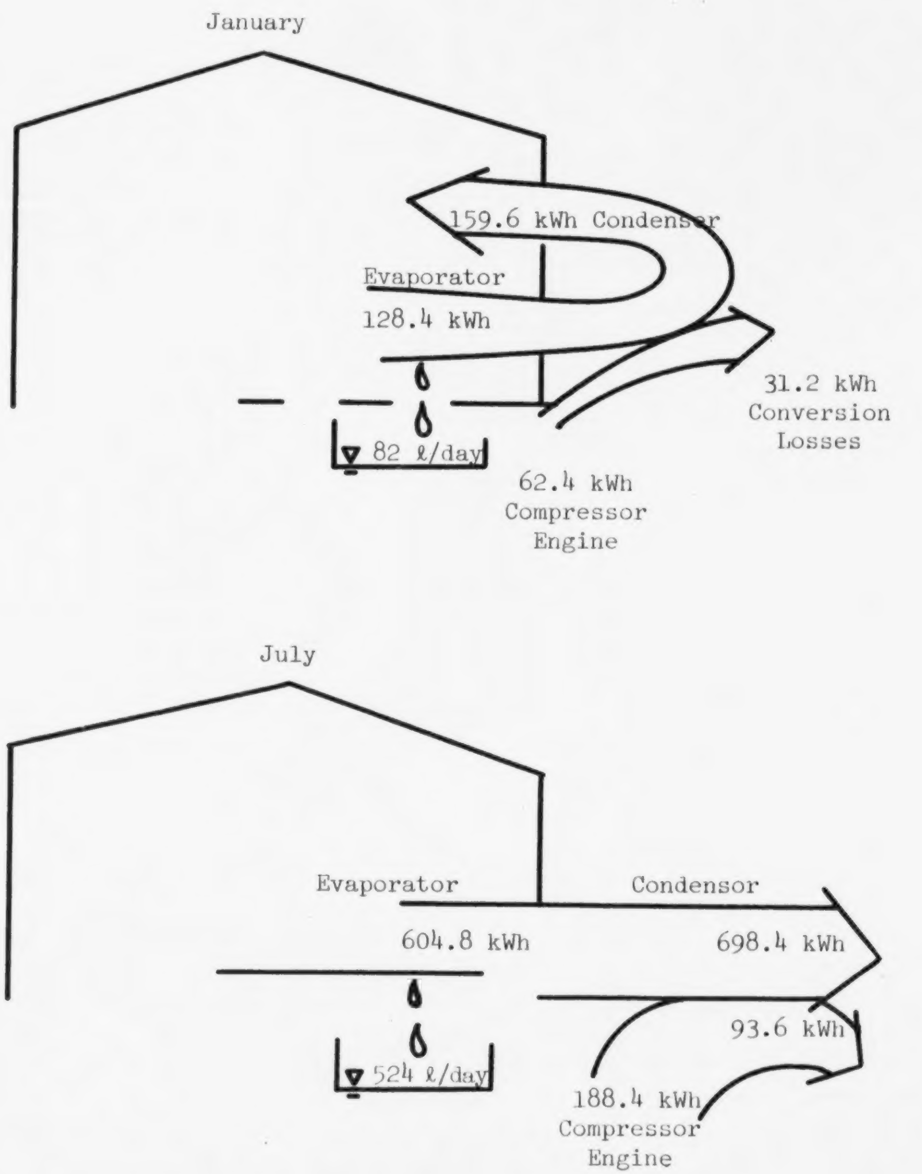

Figure 7.59. Energy balance for the refrigerative compression system.

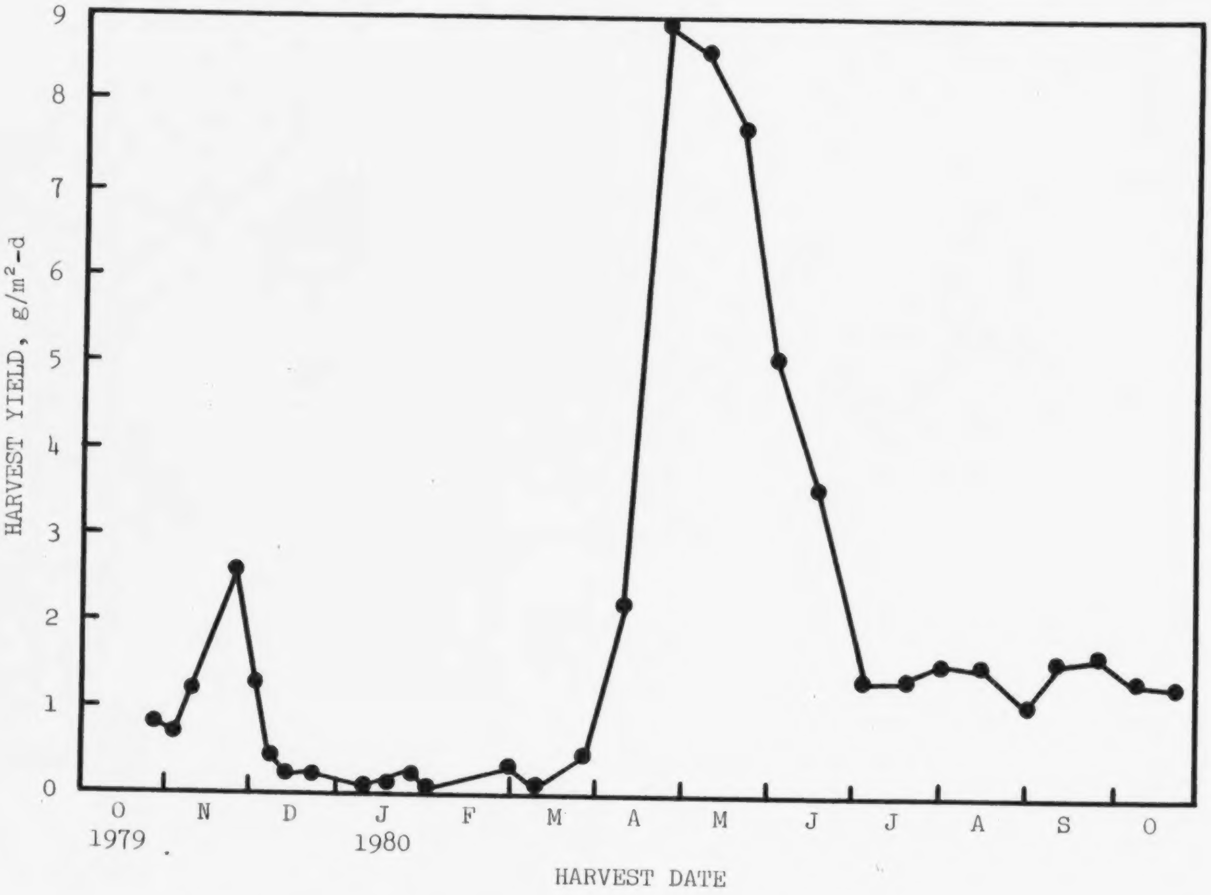

Figure 7.60. Dry weight harvest yield of a 9.3 m² reed canary grass control unit.

TABLE 7.10. DATES, YIELDS, DRY WEIGHTS AND NUTRIENT CONTENTS OF AGED CANARY GRASS HARVESTS IN THE CORNELL BRACEHOUSE UNIT #2. THIS UNIT WAS GROWN FROM SEED AND USED AS A CONTROL.

Date	Yield g	Dry Wt. %	N %	P %	Cd µg/g	Dry Weight g/m^2-d
10/18/79	1072	15.6				
10/26/79	274	18.2				0.766
11/1/79	326	11.5				0.672
11/8/79	589	13.5				1.221
11/15/79	--	-				--
11/22/79	1176	14.1				2.547
11/29/79	602	14.1				1.304
12/6/79	149	14.3				0.327
12/13/79	95	13.8				0.201
12/20/79	69	18.5				0.196
1/8/80	39	16.2				0.036
1/17/80	57	19.3				0.131
1/25/80	71	23.0				0.219
1/31/80	66	7.9				0.093
2/8/80	--	--				--
2/14/80	--	--				--
2/21/80	--	--				--
2/28/80	62	24.0				0.229
3/7/80	67	7.4				0.076
3/27/80	506	17.6	5.28	.65	.35	0.479
4/10/80	2050	13.6	5.26	.61	.37	2.141
4/24/80	6850	17.0	4.74	.53	.33	8.944
5/8/80	6776	16.6	4.09	.51	.42	8.639

(continued)

TABLE 7.10 (continued). DATES, YIELDS, DRY WEIGHTS AND NUTRIENT CONTENTS OF AGED CANARY GRASS HARVESTS IN THE CORNELL BRACEHOUSE UNIT #2. THIS UNIT WAS GROWN FROM SEED AND USED AS A CONTROL.

Date	Yield g	Dry Wt. %	N %	P %	Cd µg/g	Dry Weight g/m^2-d
5/22/80	5630	14.2	4.74	.56	.51	7.719
6/3/80	4508	15.3	4.89	.50	.52	4.999
6/19/80	3389	16.5	5.14	.56	.38	3.592
7/13/80	1227	13.8	4.09	.50	.52	1.301
7/17/80	958	19.0	4.17	.52	.42	1.398
7/31/80	996	19.8	4.00	.40	.32	1.515
8/14/80	959	20.1	3.62	.49	.41	1.480
8/29/80	895	16.7	4.45	.65	.60	1.071
9/11/80	835	21.9	4.31	.65	.97	1.513
9/26/80	1440	15.1	4.86	.67	.66	1.670
10/9/80	1160	14.5	5.03	.70	.75	1.391
10/23/80	1067	16.3	4.27	.65	.88	1.336
11/10/80	436	17.0	5.03	.65	1.13	.443

TABLE 7.11. DATES, YIELDS, DRY WEIGHTS AND NUTRIENTS CONTENTS OF REED CANARY GRASS HARVESTS IN THE CORNELL BRACE HOUSE UNIT #4. THIS UNIT WAS THE PRIMARY TEST UNIT IN EARLY EXPERIMENTS AND SERVED AS THE ET CONTROL IN LATER EXPERIMENTS.

Date	Yield g	Dry Wt. %	N %	P %	Cd µg/g	Dry Weight g/m^2-d
10/8/79	4320	--				
10/18/79	1615	22.4				3.890
10/25/79	440	15.1				1.021
11/1/79	156	15.1				0.362
11/8/79	235	15.1				0.545
11/15/79	137	15.0				0.316
11/22/79	138	17.1				0.362
11/29/79	160	16.8				0.413
12/6/79	171	15.7				0.413
12/13/79	143	16.5				0.362
12/20/79	60	19.0				0.175
1/8/80	90	20.0				0.102
1/17/80	--	--				--
1/25/80	64	20.4				0.175
1/31/80	79	24.0				0.340
2/8/80	--	--				--
2/14/80	69	21.0				0.260
2/21/80	107	19.0				0.312
2/28/80	147	19.0				0.429
3/7/80	251	22.0				0.848
3/20/80	706	17.8	5.62	.61	2.02	1.039
4/3/80	1450	15.6	4.47	.69	.67	1.737

(continued)

TABLE 7.11 (continued). DATES, YIELDS, DRY WEIGHTS AND NUTRIENT CONTENTS OF REED CANARY GRASS HARVESTS IN THE CORNELL BRACEHOUSE UNIT #4. THIS UNIT WAS THE PRIMARY TEST UNIT IN EARLY EXPERIMENTS AND SERVED AS THE ET CONTROL IN LATER EXPERIMENTS.

Date	Yield g	Dry Wt. %	N %	P %	Cd µg/g	Dry Weight g/m^2-d
4/17/80	4912	13.3	4.87	.65	1.00	5.018
5/1/80	7470	14.9	5.01	.63	.63	8.549
5/15/80	4750	14.6	4.47	.56	.94	5.326
5/29/80	3530	18.9	--	--	--	5.124
6/12/80	2695	15.4	4.63	.62	.64	3.188
6/26/80	1142	18.5	4.97	.53	.22	1.623
7/10/80	1823	--	4.41	.58	.74	2.681
7/24/80	1216	19.8	4.52	.53	.29	1.849
8/7/80	1263	17.1	4.35	.67	2.16	1.659
8/21/80	1792	14.9	4.25	.77	.37	2.051
9/8/80	1115	17.7	4.43	.66	6.31	1.179
9/18/80	1749	15.2	5.03	.72	4.37	2.859
10/2/80	2219	14.6	5.50	.73	1.35	2.488
10/16/80	2864	13.3	5.08	.76	4.43	2.926
10/30/80	1232	13.0	4.95	.72	2.73	1.230
11/13/80	288	14.0	6.42	.73	1.62	0.310
12/18/80	272	--				0.131
1/22/81	78	17.4				0.042
3/12/81	1867	16.0	4.91	.68	3.45	0.656
4/17/81	7976	15.9	4.36	.58	2.33	3.788
6/3/81	—	18.6	2.79	.49	2.91	--
7/10/81	7200	25.4	2.45	.33	2.03	5.315

TABLE 7.12. DATES, YIELDS, DRY WEIGHTS AND NUTRIENT CONTENTS OF REED CANARY GRASS HARVESTS IN THE CORNELL BRACEHOUSE UNIT #3. THIS UNIT WAS A CONTROL UNIT IN EARLY EXPERIMENTS AND WAS PART OF 18.6 m^2 SYSTEMS LATER.

Date	Yield g	Dry Wt. %	N %	P %	Cd µg/g	Dry Weight g/m^2-d
10/6/79	—	--				
10/18/79	1370	18.9				2.320
10/26/79	398	17.4				1.064
11/1/79	179	14.2				0.456
11/8/79	787	12.1				1.463
11/15/79	--	--				--
11/22/79	557	10.7				0.915
11/29/79	1197	11.4				2.096
12/6/79	265	13.2				0.537
12/13/79	110	20.6				0.348
12/20/79	69	17.5				0.185
1/8/80	209	20.0				0.237
1/17/80	187	17.7				0.395
1/25/80	1018	16.0				2.189
1/31/80	110	25.0				0.493
2/8/80	--	--				--
2/14/80	80	22.0				0.315
2/21/80	113	19.0				0.330
6/12/80	1840	13.8	4.19	.44	.61	--
6/26/80	4600	17.0	4.97	.53	.22	6.006
7/10/80	3665	--	3.74	.53	.33	5.123
7/24/80	2088	19.4	4.98	.66	1.33	3.111

(continued)

TABLE 7.12 (continued). DATES, YIELDS, DRY WEIGHTS AND NUTRIENT CONTENTS OF REED CANARY GRASS HARVESTS IN THE CORNELL BRACEHOUSE UNIT #3. THIS UNIT WAS A CONTROL UNIT IN EARLY EXPERIMENTS AND WAS PART OF 18.6 m^2 SYSTEMS LATER.

Date	Yield g	Dry Wt. %	N %	P %	Cd μg/g	Dry Weight g/m^2-d
8/7/80	1703	16.3	4.01	.60	.50	2.132
8/21/80	2541	16.9	4.18	.67	.47	3.298
9/8/80	1568	19.9	4.65	.75	.57	1.864
9/18/80	2085	21.4	3.83	.53	3.89	4.798
10/2/80	1709	16.7	4.53	.56	1.06	2.192
10/16/80	1108	13.9	4.86	.72	1.08	1.183
10/30/80	416	15.3	5.60	.73	2.68	0.489
11/13/80	70	13.2	5.41	.71	1.38	0.071
12/18/80	40	--	--	--	--	--
1/22/81	17	4.2	--	--	--	--

TABLE 7.13. HARVEST DATA FROM THE CRREL GREENHOUSE WHICH GREW CANARY GRASS IN 7.4 m^2 UNITS (TOTAL).

Date	Unit	Yield g	Dry Wt. %	Dry Yield g	N %	P %	Dry Wt. g/m^2-d	N Removal Rate kg/ha-d	P Removal Rate kg/ha-d
3/3/80	A	1814	14	254	6.0	0.76			
	B	1588	15	238	5.8	0.77			
	Total	3402	14	492	5.9	0.76	2.4	1.39	0.18
				(Avg.)	5.8	0.76			
3/18/80	A	1361	13.5	184	6.1	0.69			
	B	1588	13	206	5.8	0.80			
	Total	2949	13	390	5.9	0.75	3.5	2.06	0.27
				(Avg.)	5.9	0.75			
4/11/80	A	3087	12.5	386	5.9	0.65			
	B	3522	12.5	440	5.4	0.76			
	Total	6609	12.5	826	5.6	0.71	4.6	2.61	0.33
				(Avg.)	5.63	0.71			

(continued)

TABLE 7.13 (continued). HARVEST DATA FROM THE CRREL GREENHOUSE WHICH GREW CANARY GRASS IN 7.4 m^2 UNITS (TOTAL).

Date	Unit	Yield g	Dry Wt. %	Dry Yield g	N %	P %	Dry Wt. g/m^2-d	N Removal Rate kg/ha-d	P Removal Rate kg/ha-d
5/1/80	A	3270	12	392	5.4	0.69			
	B	2720	12	326	5.4	0.74			
	Total	5990	12	718	5.4	0.71	4.8	2.61	0.34
				(Avg.)	5.4	0.71			
5/22/80	A	3521	13	458					
	B	3049	13.5	412					
	Total	6570	13	870			5.6		
				(Avg.)	5.4	0.71		(3.01)	(0.40)
6/17/80	A	1848	15.5	286					
	B	2513	15.5	390					
	Total	4361	15.5	676			3.5		
				(Avg.)	5.4	0.71		(1.92)	(0.25)

Parenthesized numbers are estimated.

TABLE 7.14. HARVEST DATA FROM HANOVER GREENHOUSE IN 1981.

Date	Species	Wet Wt. g	Dry Wt. %
3/20/81	Canary Grass	7878	35.9
4/13/81	Canary Grass	6603	15.5
5/8/81	Canary Grass	8555	14.8
5/14/81	Phragmites	271[1]	26.5
5/14/81	Phragmites	541[2]	24.6
6/3/81	Canary Grass	3435	15.9
6/3/81	Phragmites	11232	20.6

[1] Upper (1.2 m^2 cut).
[2] Lower (1.2 m^2 cut).

Some of the nutrient uptake data with the synthetic sewage studies are illustrated in Table 7.13. A smaller amount of information is available for the domestic sewage studies. However, this information does illustrate several comparisons. First, it should be emphasized that none of the experiments represented optimum yields since the focus was on BOD and suspended solids removal. No yield information was taken during the Cayuga Heights sewage studies. Under all high rate loading conditions with the sewage units large amounts of organic suspended solids were present that tended to inhibit growth of all species. Subsequent tests should be conducted using high yielding plants such as napier grass downstream of the sewage units after the BOD and suspended solids have been removed in the high loading rate unit. Discussion of the cadmium concentration and other heavy metals will be included in a subsequent section on toxic constituent concentrations.

F. PLANT CULTURING AND PROPAGATION FOR ESTABLISHING AND OPERATING AN NFT SYSTEM

F.1. Culture of Species in Total Controlled Environments

The objective of the cultural task was to identify techniques for rapid propagation of large quantitites of the selected species. From these tests, the essential characteristics of either the propagation system and/or the plant itself was to provide rapid germination and some protection to the root from direct sunlight. Sunlight promotes algal growth that inhibits rapid root development. Experiments conducted by General Electric Company were in a highly artificial environment (controlled temperature, light intensity and duration, humidity and carbon dioxide concentration) that would not be considered for application to wastewater treatment. However, propagation experiments can be used to approximate less controlled conditions. All yields and nutrient uptakes will be significantly less in conventional greenhouses. All species rooted rapidly when provided with narrow strips of shade at varying widths (the width depended on the species). Root development was rapid in shade, shoot growth followed, and shading by the shoot quickly eliminated the algal growth. This sequence held for all species except the cattails, which were not inhibited by algal growth. Figure 7.61 indicates the extent of the algal growth on newly germinated seedlings. Watercress is shown in Figures 7.62 and 7.63 before and after the sixth harvest.

A subsequent set of trials involved propagation by plugs of the reed canary grass, coastal Bermuda grass, and watercress. The plugs were separated by various distances; spacing of up to twice the diameter of the plugs produced rapid filling of the interspaces (see Figure 7.64). This proved to be a successful method of propagation.

Napier grass cuttings are shown as received in Figure 7.65. The rapid response is dramatically indicated in Figure 7.66 and 7.67. Comparisons of characteristics of roots of the species are shown in Figures 7.68 to 7.71. It is clear from these root observations that several of these species may have a role in wastewater treatment.

The cultural experiment series in the controlled environment greenhouse succeeded in establishing a crop of each plant species in six weeks or less. Healthy plants with vigorous and extensive root systems were maintained through several harvests.

F.1.a. Nutrient Removal in Total Controlled Environmental Greenhouses--

Each of the crop stands was propagated in a low nutrient solution, similar to a half strength Hoagland's solution (Hoagland and Arnon, 1950). When active growth was evident the crops were given a full strength nutrient solution such as is used in hydroponic operations. Once stand establishment was assured, nutrient levels were reduced to those indicate in Table 7.15.

An example of nutrient disappearance for the baseline species is shown in Figure 7.72 (see Appendix for other experiments). Exact bed areas and volumes of recirculating nutrient solution are indicated on the respective figures. For reed canary grass, napier grass, and watercress in excess of 1 g/m^2 nitrogen disappeared within 24 hours of application (vol = 230 ℓ; 230 x 30 ppm = 6.9 g per 6 m^2 bed area). The linearity of the nitrogen removal down to less than 1 ppm is also apparent. Removal of phosphorous was also very efficient; the time required for removal was slightly longer. It is also clear that the species operate with different efficiencies. Reed canary grass and napier grass were more efficient in the removal of phosphorous than the other species; bermuda grass efficiency was generally disappointing.

F.1.b. Biomass Production--

Biomass yield records were maintained since the first harvests of the crops. Computation of dry weight biomass yields is shown in Table 7.16 and extrapolated to annual productivities.

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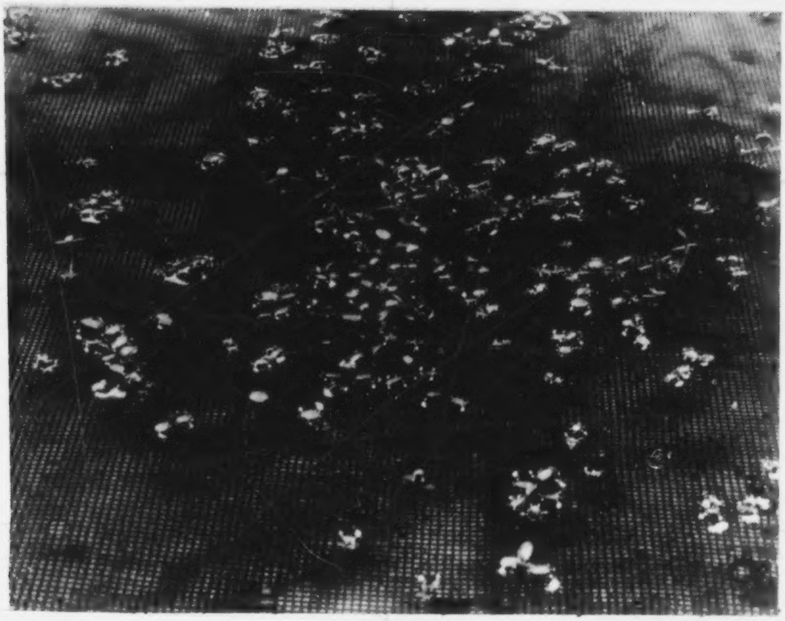

Figure 7.61. Plant seedlings growing on mat in NFT trough. Darkened areas around roots are algal growth.

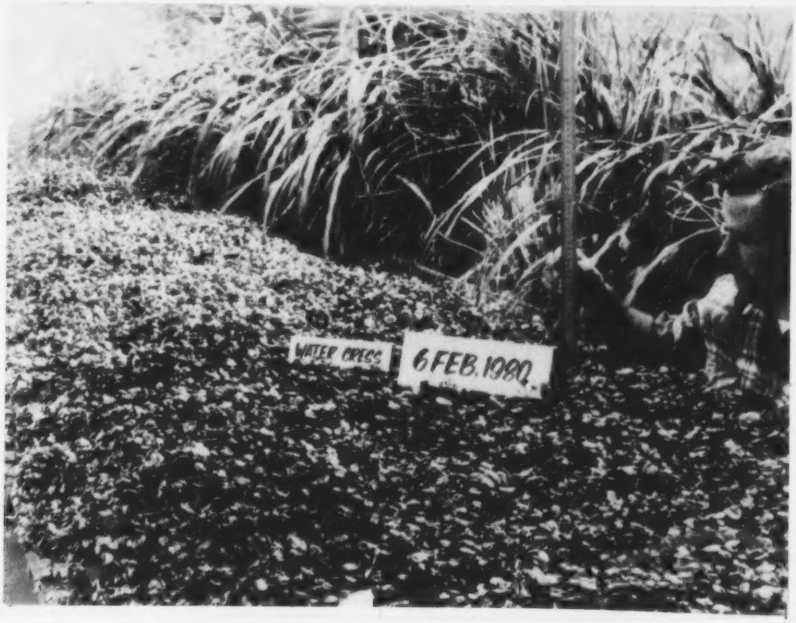

Figure 7.62. Growth of watercress before biweekly harvest. Plants grew to 20 cm above bed floor.

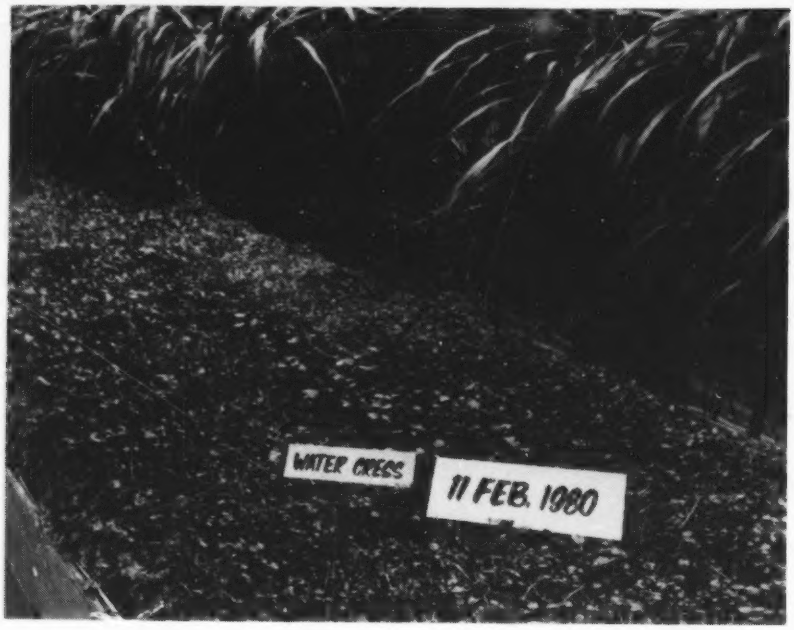

Figure 7.63. Stand of watercress after biweekly harvest.

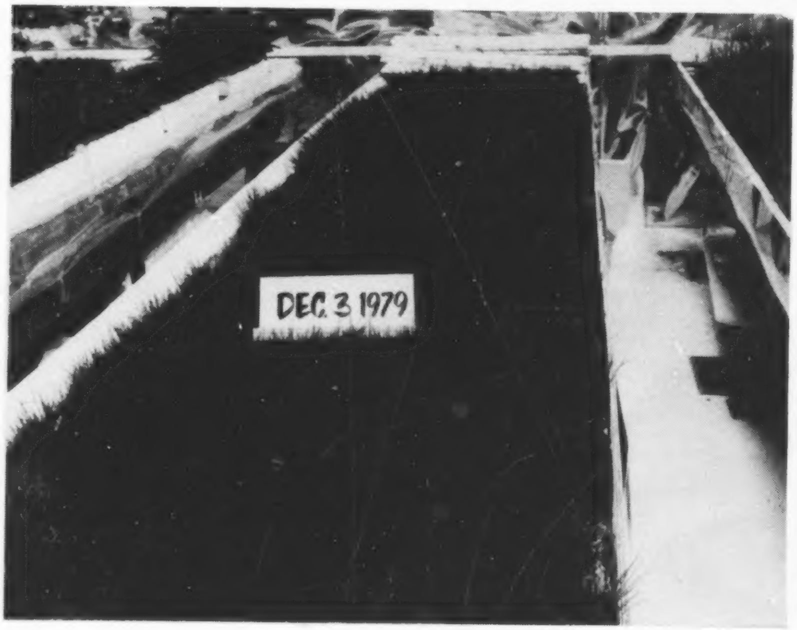

Figure 7.64. Stand of reed canary grass grown from plugs. Note that grass has filled in areas between plugs, thus expanding the root mat and limiting algal production.

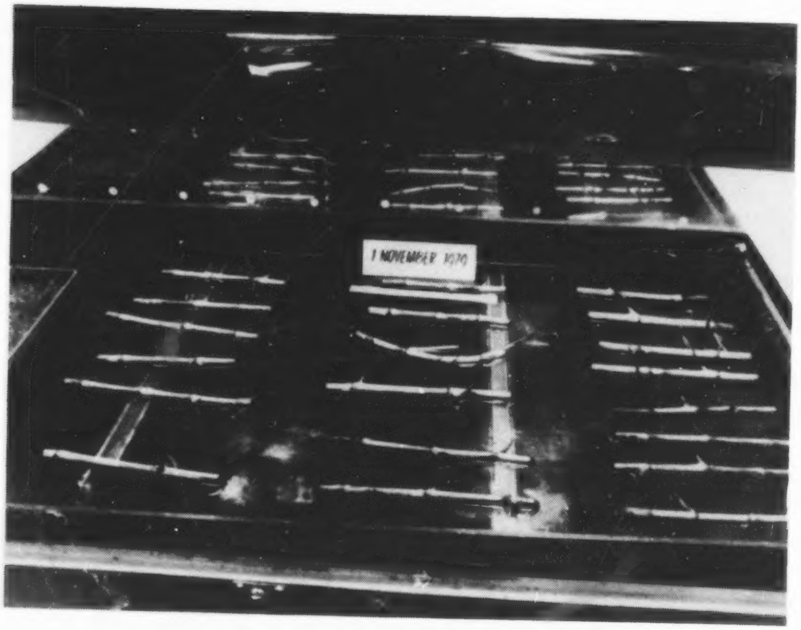

Figure 7.65. Napier grass cutting at initial transplant into the NFT trough.

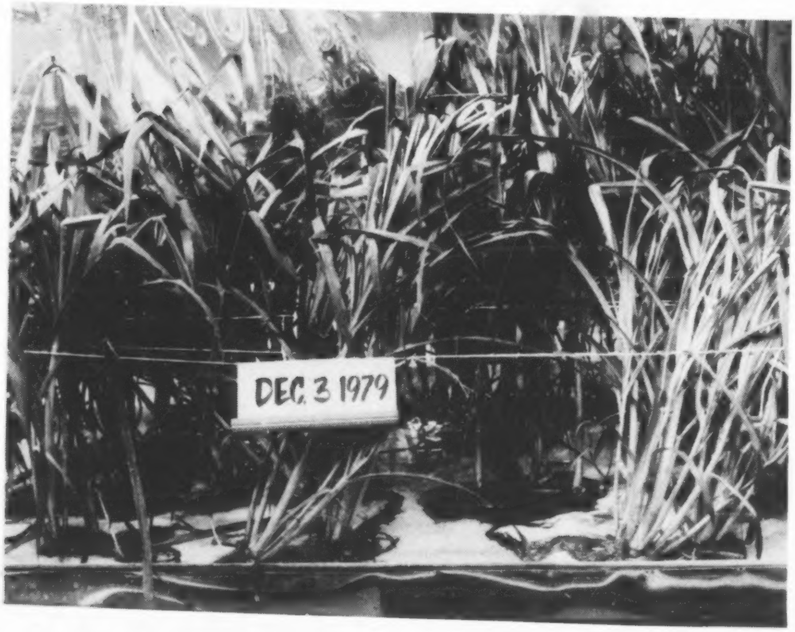

Figure 7.66. Napier grass stand at time of move to larger bed.

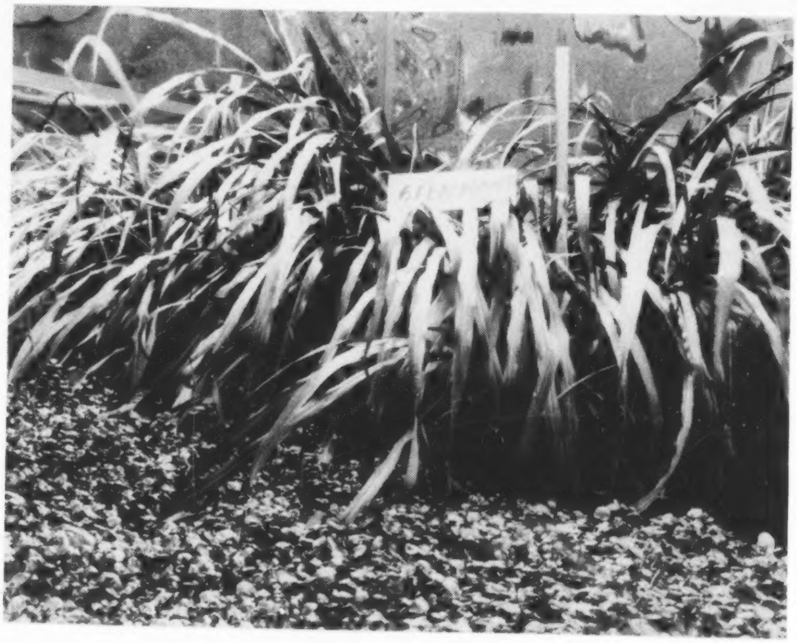

Figure 7.67. Regrowth of napier grass three weeks after first harvest.

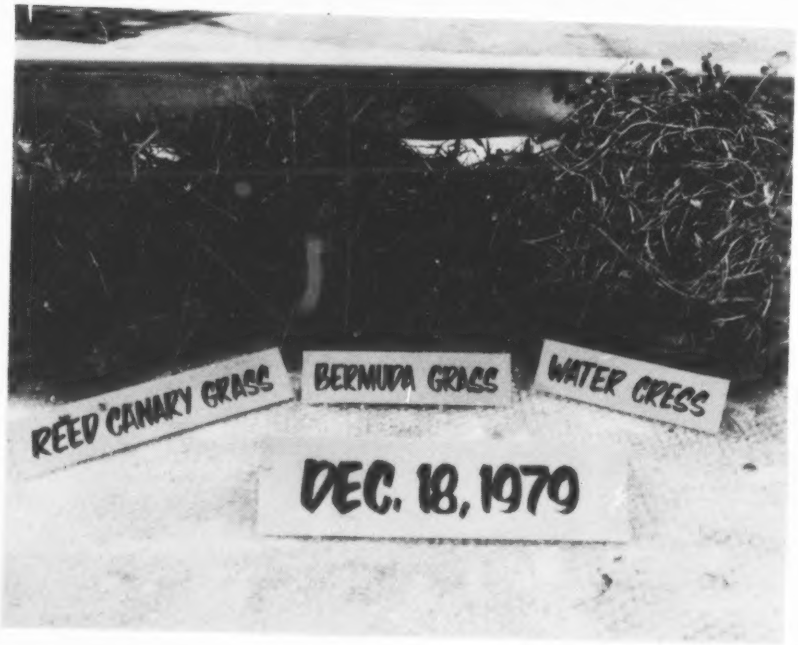

Figure 7.68. Side view of root mats of reed canary grass, coastal Bermuda grass, and water cress grown in NFT trough.

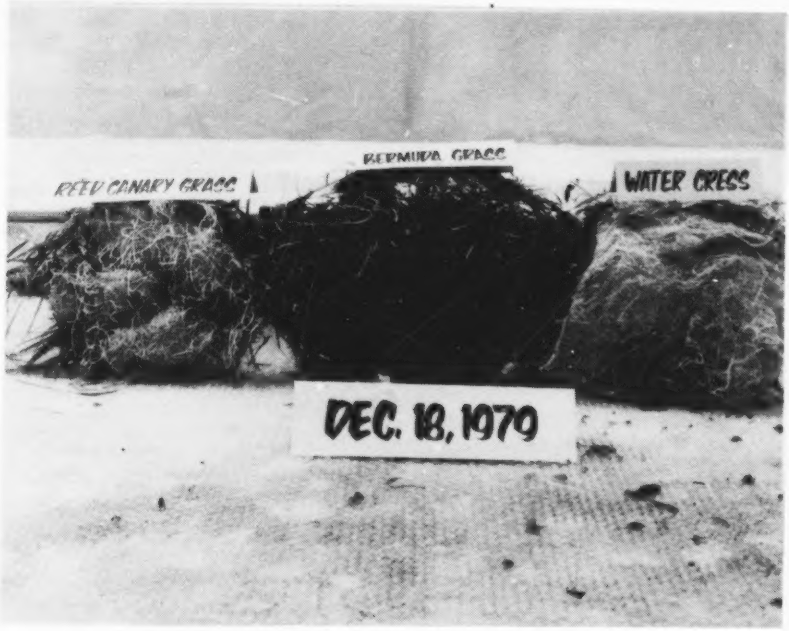

Figure 7.69. Bottom view of root mats of reed canary grass, coastal Bermuda grass, and water cress grown in NFT trough.

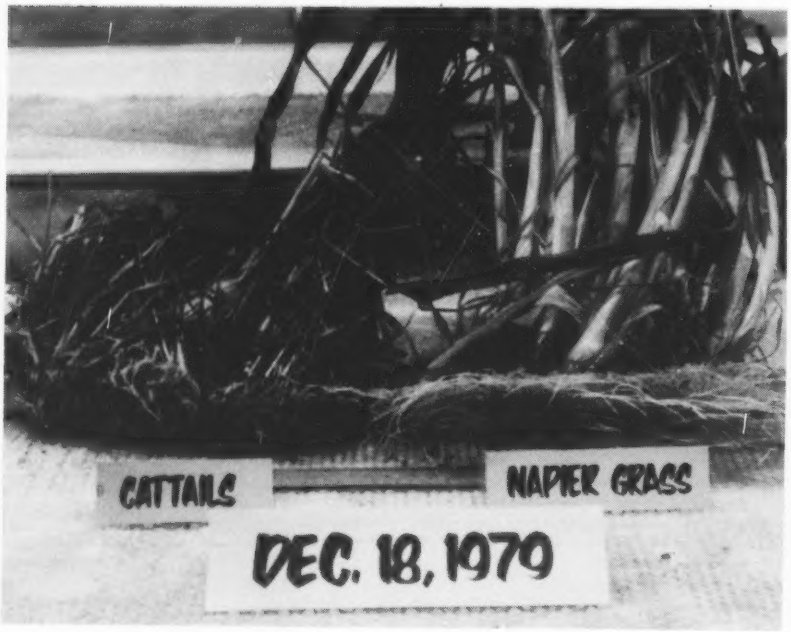

Figure 7.70. Side view of root mats of cattails and napier grass grown in NFT trough.

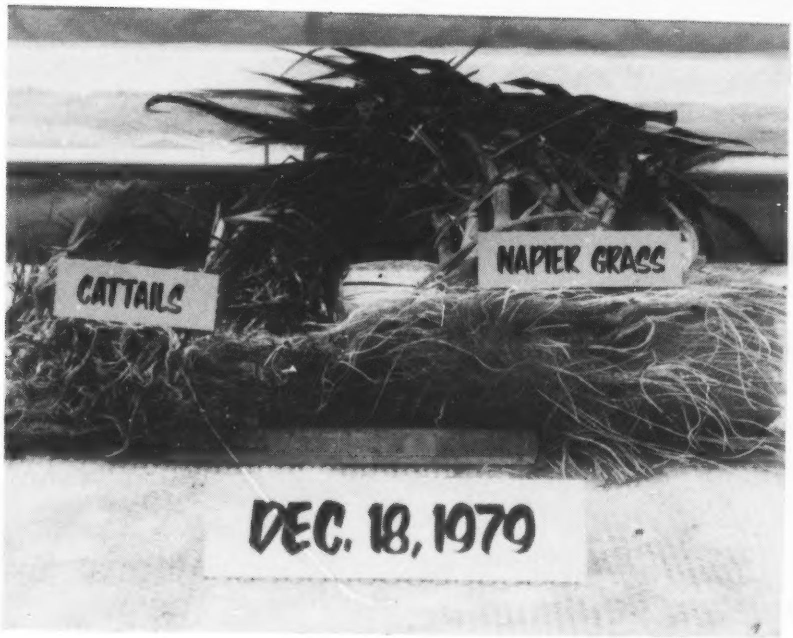

Figure 7.71. Bottom view of root mats of cattails and napier grass grown in NFT trough.

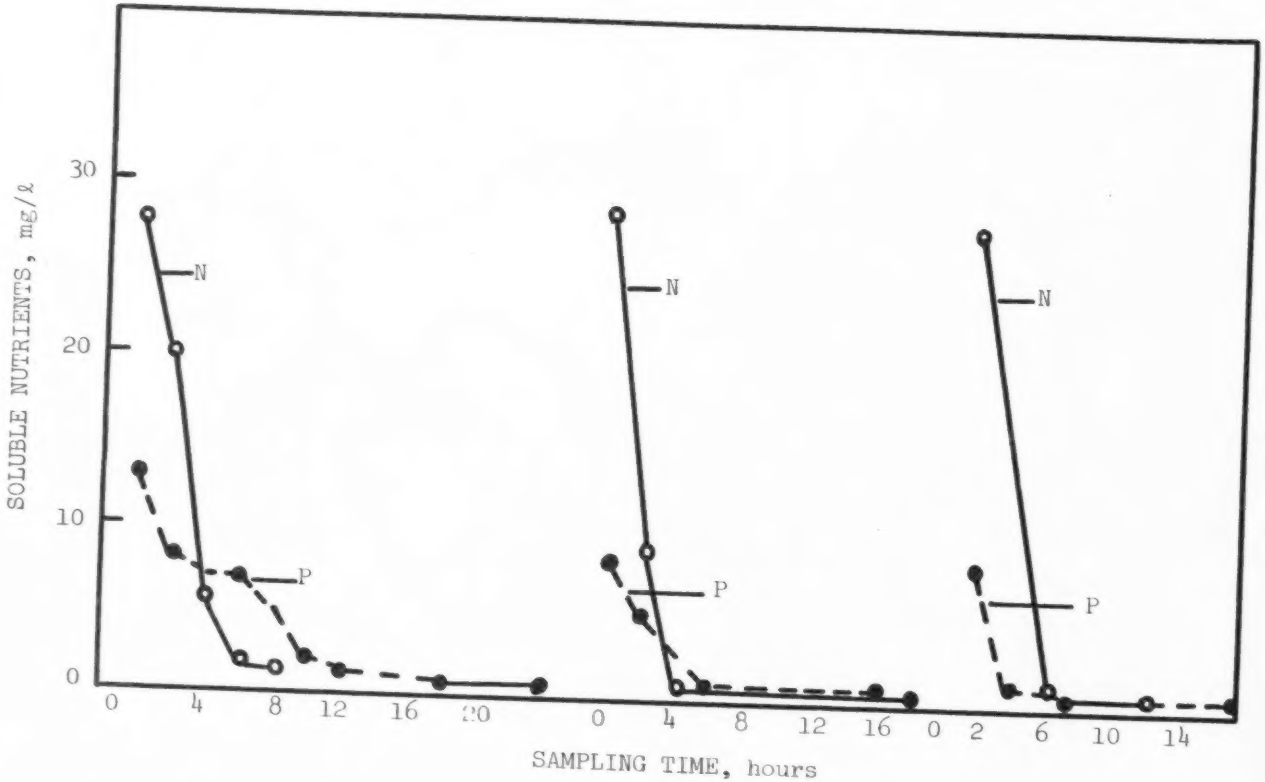

Figure 7.72. Nitrogen and phosphorus removals from General Electric NFT unit containing reed canary grass.

TABLE 7.15. GRASS NUTRIENT FORMULA USED IN PLANT PROPAGATION IN TOTAL CONTROLLED ENVIRONMENT

Constituent	Nutrient	Concentration (mg/ℓ)
$Ca(NO_3)_2 4H_2O$	Calcium	45
	Nitrogen	40
KH_2PO_4	Potassium	12
	Phosphorous	10
$MgSO_4 \cdot 7H_2O$	Magnesium	5
	Sulfur	7
FeDTPA	Iron	0.1
$MnSO_4H_2O$	Manganese	1.0
H_3BO_3	Boron	0.2
$(NH_4)_6Mo_7O_{24}4H_2O$	Molybdenum	0.05
$ZnSO_4 \cdot 7H_2O$	Zinc	0.1
$CuSO_4 5H_2O$	Copper	0.1

TABLE 7.16. BIOMASS YIELD OF TEST SPECIES SHOOT HARVEST

Species	Yield, Wet Wt. kg/m^2-wk	Dry Weight Fraction	Dry Weight Yield		
			kg/m^2-wk	g/m^2-d	tonnes/ha-yr
Napier	3.55	.083	.29	41.5	150
Watercress	0.92	.066	.061	8.7	32
Bermuda Grass	0.1	.20	.02	2.9	10.4
Reed Canary Grass	0.61	.15	.09	12.8	46.9
Cattails	2.21	.048	.106	15.2	55.3

F.2. Culture of Species in Greenhouses

The response of plants placed in NFT units varied according to the environmental conditions in the greenhouses and the solutions into which they were placed. The wetland plants and some terrestrial plants were placed in noncarbonaceous nutrient solution in Ken Post greenhouses in the fall of 1980 and are discussed first. Other terrestrial plants were later cultivated in this clean solution. Many of the wetland plants, along with flower and vegetable plants, were transported to Hanover and tested on sewage; and these are discussed later in this section.

F.2.a. Response to Non-Carbonaceous Nutrient Solution--

The plant species placed in the NFT units exhibited a variety of growth responses, from practically no growth to luxurious growth. Accordingly, the species were evaluated on the basis of top growth and root development and were assigned to one of the following categories:

1. species that flourished;
2. species with marginal growth;
3. species that died or failed to form new growth.

Table 7.17 summarizes the overall responses of different plants to the nutrient solution. It should be noted that the species were rated based on growth during the short-day conditions of autumn and winter. If the plants had been grown throughout the summer months, higher productivity would have been expected. The value of conducting autumn and winter tests, however, was that the species experiencing a period of dormancy could be distinguished from those that grew continuously. It should be made clear that these listings are based on survival performance in NFT systems. When nutrient levels are lower than those used in this study, plant performance may be affected. Similarly at high loadings of sewage, plant response could be quite different.

Species that Flourished--Among all plant species grown in the units, none surpassed the vigorous growth of napier grass. Grown from cuttings, this species rapidly developed a thick root mat and dense top growth. A colony of the grass may be rapidly increased in size by propagating shoot cuttings.

Reed canary grass grew very well, even after repeated top growth harvests. The root mat was well developed. This species is exceedingly common in wetlands of the Northeast, so wild stock is readily available for transplanting purposes. Also, the plant was easily established from seed in the greenhouse.

Although the shoots of phragmites grew well, shoot density and vigor was not equal to that of napier grass. Roots developed into a relatively thin mat and new shoots were produced from rhizomes. Following a winter harvest of the shoots, the plants at first responded slowly but eventually developed new shoots from the rhizomes. As day length increased in the spring, phragmites grew rapidly and developed a more extensive root mat.

Soft rush continuously produced new shoots through the winter months and developed a thick root mat. Although the plants were relatively low in stature (<50 cm), shoot density was high. During spring and summer plant vigor declined until little or no new shoot growth was produced. The reasons for this plant's condition at that time are unclear.

Lake sedge experienced good growth during autumn but grew slowly during winter. The root mat was relatively thin. Spring and summer growth was relatively poor.

Softstem bulrush grew well initially but responded very slowly following a harvest of the shoots. The shoots of this species, therefore, should not be harvested until they attain full development.

TABLE 7.17. PLANT RESPONSE TO NUTRIENT SOLUTIONS

Category	Species
Species that flourished	Napier grass Reed canary grass Phragmites Soft rush Lake sedge Softstem bulrush Roses Geraniums Petunias
Species with marginal growth	Japanese millet Bristly sedge Cattails Sugar cane Eastern cottonwood Arrow aram Cucumbers Carnations Blackberry
Species that died or failed to grow	Wild rice Swamp loosestrife Woolgrass Lizardtail

Three ornamental species performed well in the NFT units. Roses, geraniums and petunias showed good top growth, root development and flower production. These plants were grown under the longer daylengths of late spring, so their performance in winter light conditions was not demonstrated; the general response of geraniums and petunias to short days is elongated stem growth. Roses, however, continued to grow well as long as the temperature remained above 15°C. Temperature stress in the form of red leaves was evident in the roses when temperatures dropped below 15°C.

Species with marginal growth--Japanese millet, an annual, established from seed, grew to maturity, but the plants were stunted (<20 cm). An established colony later, however, grew much more vigorously than the first colony, suggesting that the plants may have been responding favorably to an increasing photoperiod. The greatest potential of this species lies in its ability to grow rapidly from seed during the summer.

Bristly sedge grew slowly during fall and winter, but did develop a fairly dense root mat. Growth in this species appeared to be limited by short day and/or low light intensity conditions. During the summer months it grew well and produced seed.

Cattail seedlings and overwintering shoots grew very slowly and seemed to be in a dormant condition due to the short photoperiod (and/or low light intensity). With increased day length, top growth improved and a fibrous root mat developed.

Sugarcane grew very slowly during the winter and did not develop a root mat. Its growth, however, improved with increased day length. Also its placement next to napier grass might have been an impediment, since napier grass quickly shaded any adjacent plant.

Although some cuttings of eastern cottonwood died, others developed lateral branches and grew fairly well. The roots were sparse and did not form a mat.

Arrow arum remained dormant until February when the increasing daylength and/or light intensity stimulated growth. Later, its leaves grew vigorously, although the root mat was not very extensive.

Cucumbers and carnations performed moderately well in the clean solution NFT unit. Like roses, cucumbers seemed subject to nutrient deficiency at higher levels of nutrients than other plants in these units; conversely, when the cucumbers grew well they grew as fast as any other plant except napier grass. Carnations grew continuously in the nutrient solution but did not produce large, high quality flowers. Stems were often elongated and did not grow erect, possibly due to shading by adjacent plants.

Rooted cuttings of blackberry bushes were grown in NFT units, but survival was poor. This was due primarily to the root configuration of the cuttings; the woody roots grew around the lower six inches of the cutting, and only a small portion of the roots was in contact with the nutrient film. The plants that survived the first few weeks grew very well, suggesting that blackberry bush production in NFT units may be successful.

Species that died or failed to grow--Wild rice seeds planted in NFT units germinated within a week, but the seedlings were spindly and few attained an erect stature. All eventually died. A large amount of algae that became established in the unit may have contributed to this failure. Possibly, this species would grow better given a longer photoperiod and/or a higher light intensity.

The rooting branch tips of swamp loosestrife grew slowly, and leaves soon began to be shed and the shoots died. The leaves were damaged by spider mites, but it is not known whether this factor contributed to the plant's demise. Had root masses been collected rather than branch tips, growth may have been better. The two species of burreed (big burreed and burreed) had overwintering shoots when they were placed in the NFT units, but did not grow. Both species were, therefore, considered unsuitable for use in the NFT units.

Wool grass and lizardtail failed to grow appreciably and appeared to be in a state of dormancy.

F.2.b. Plant Response to Sewage in NFT Systems—

Plants in the Hanover greenhouse were grown in sewage. Their growth responses were in many ways similar to the plants grown on nutrient solution. Overall, however, the sewage loading proved to be a harsher treatment. The plants were again rated in three categories, from those that flourished to those that died, and this categorization is presented in Table 7.18. Because the test unit was 36.6 meters long, a plant's position in the unit may have had some effect on that plant's survival and growth. After some plants were grown in the NFT unit some were planted in standard potting mixtures to determine whether plants could either recover from pathologies suffered in the unit or flourish in pots suitable for market. Plant growth in sewage and recovery of the plants following stressful periods are discussed in the following sections.

TABLE 7.18. PLANT RESPONSE TO SEWAGE

Category	Species
Species that flourished	Cattails Bulrush Strawflowers Japanese millet Roses Napier grass Marigolds Wheat Phragmites
Species with marginal growth	Bristly sedge Chrysanthemums Carnations Tomatoes Comfrey Reed canary grass Soft rush Cucumbers
Species that dies or failed to grow	Lantana Gernaniums Fuchsia Petunias

Species that flourished--Cattails began to grow rapidly after they were introduced to the NFT unit in February. Figure 7.73 shows cattails as well as other plants which responded well. Roots and shoots appeared healthy throughout the testing period and reached heights of 2 meters. They responded to harvesting well, even when a second harvest was conducted on the same plants. Cattails which were cut back resumed growth and were eventually indistinguishable from those not cut. Although cattails grown in synthetic wastewater at Cornell flowered profusely, cattails grown in sewage never flowered.

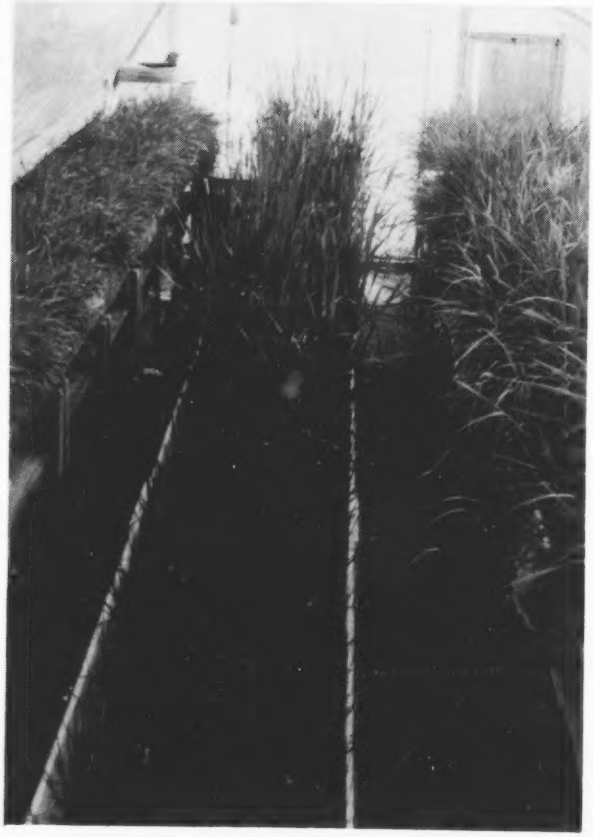

Figure 7.73. Cattail, bulrush, phragmites, and canary grass growing well in the Bracehouse 36.6 meter system.

Bulrush exhibited slow growth under low light conditions (February and early March), but rapid growth began and continued thereafter. Most shoots reached a meter or longer in height and flowered. Upon harvesting the cut stems died and were replaced by new growth emerging from the rhizomes. Over the course of testing, the plants developed a thick stand.

Strawflowers grew very well, producing stems over 60 centimeters tall and large flower heads. The plants appeared very healthy, showing no signs of insect damage or root rot.

Japanese millet performed well and showed an interesting phenomenon. Where a gradient of film depth was present (due to an unlevel unit) the taller plants were produced on the shallower film areas. Overall the millet grew rapidly and produced a large quantity of seed, although this species in the field may grow somewhat taller (Rawinski, 1981). The root system developed an extensive mat, particularly in the shallower areas.

Roses grew well in the sewage. When flower buds were cut the plants continued to grow and produce flowers. Rose cuttings in peat pots developed some adventitious roots projecting from the pots above the film surface (see Figure 7.74). Roots above the sewage appeared healthier than those below it. Following a severe infestation of spider mites, plants developed new leaves and shoots, and resumed growth.

Just as in the nutrient solution, napier grass grew vigorously. A thick root mat developed rapidly such that the root zone was never completely submerged although the mat itself raised the water level. Tall stems were cut in one-node sections and placed in sewage for rooting, which occurred within two weeks. The cut stems continued growing from branches at the lower nodes, and these new stems eventually produced inflorescences.

Marigolds flourished in the sewage, putting out new leaves, increasing in height and flowering. The root system developed well and appeared healthy.

Wheat established a healthy stand 20 centimeters tall in about two weeks (starting from sprouted seed). The root system was developing into a fibrous mat.

Phragmites grew slowly in early spring but grew much more rapidly later. The position of phragmites in the system was changed, which also affected its vigor. It responded well to cutting, showing a rapid regrowth. Roots formed a dense mat around the rhizomes and raised the entire plants.

Species with Marginal Growth--Bristly sedge had considerable top growth and healthy roots. In late spring it went to seed, and leaves turned brown at the tips. After producing seed new leaves continued to grow while older ones continued to brown.

Chrysanthemums grew well initially, but at the initiation of flowering the plants suffered a severe aphid infestation and root death. Peat pots were removed from the roots and buds were removed from the stems, but the plants showed little improvement. The buds did not grow and the plants barely

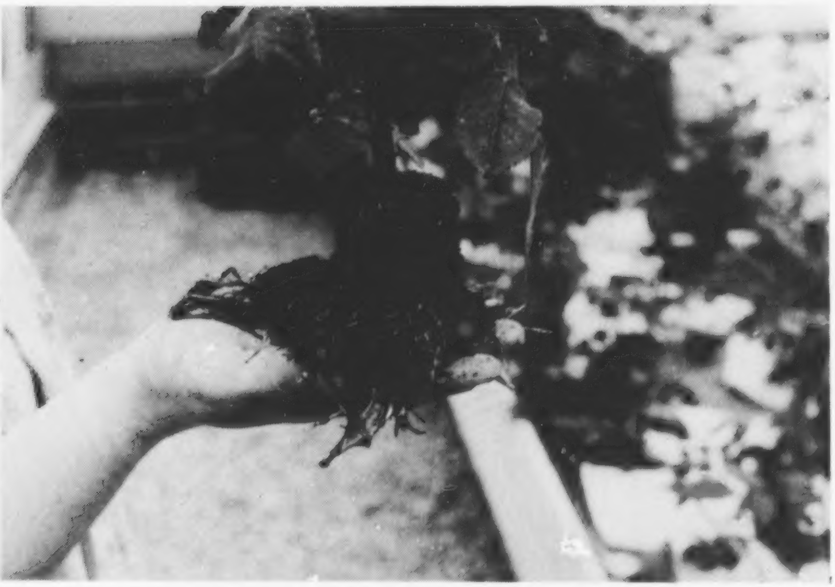

Figure 7.74. Root zone of a rose in peat pot showing anoxic accumulations at bottom.

survived. Because this plant has a very strong reaction to photoperiod, it might have performed much better in the summer.

Carnations were similar to the mums in that their initial growth was good, but they soon suffered from rotting roots. There was some regrowth after flower buds were removed. The peat pots were again suspected of causing problems and were removed, but only small growth in roots was noted.

Initially, the tomatoes showed healthy roots and vegetative growth. As the plants began flowering and setting fruit, lower leaves began turning brown and died. Roots were never extensive but in latter stages of fruit production they turned gray. The fruit ripened when still very small.

Comfrey wilted when it was first put in the unit but later sent out new leaves and appeared healthy.

Reed canary grass grew very well through the lower loading rates tested (6.9 and 10.2 centimeters per day). Toward the end of the 20.3 centimeter inch per day loading much of the grass had died and the productivity of the remaining grass was quite low. Under these conditions, new leaves in the grass were rare, and much of the root mat was black and rotten. It appeared that many solids from upper parts of the system had been washed down and trapped by the canary grass's finer root system. The grass was flushed with tap water for several days to remove solids, after which the system was operated at a low 5.1 centimeter per day loading. The grass remained viable and recovered slowly at this low condition.

Soft rush appeared to be in dormancy until late April. Prior to that time much of it had degenerated and was discarded as dead. The remaining plants appeared healthy and had firm white roots.

Cucumbers, when first placed in the unit in February, responded with vigorous growth. Good shoot and root development and flowering with subsequent fruit were noted. When the loading rate was increased from 6.9 to 10.2 centimeters per day, roots deteriorated rapidly which was followed by the degeneration of plant tops (see Figures 7.75 and 7.76). The plants were removed from the unit when appearing nearly dead. A second set of cucumbers were introduced to the unit but did equally poorly, and all eventually died.

Species that Died or Failed to Grow--Lantana flowered immediately upon placement in the unit but produced only small leaves and a very small root system.

Geraniums were the first species to show signs of failure. Leaves yellowed and dropped, and roots deteriorated quickly. The poorest performance among geraniums was noted for those planted in the greatest depth of sewage. Attempts to culture geraniums without peat pots gave the same results. Plants flowered continuously, but leaves produced were very small. Root growth or regeneration was minimal.

Fuchsia grew well initially but then degenerated rapidly. Plants lost leaves with no new production.

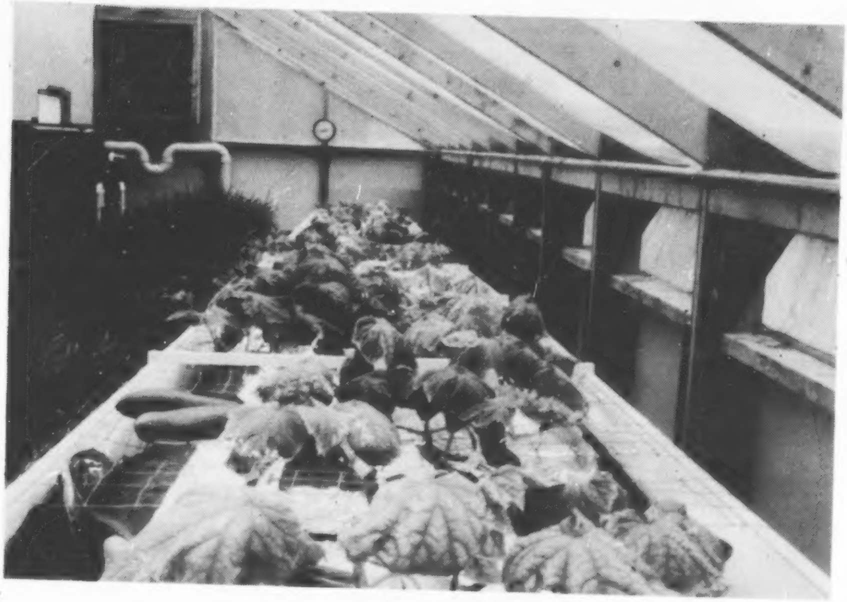

Figure 7.75. Hanover units containing cucumbers during early testing of the large unit. Note stressful condition of plants.

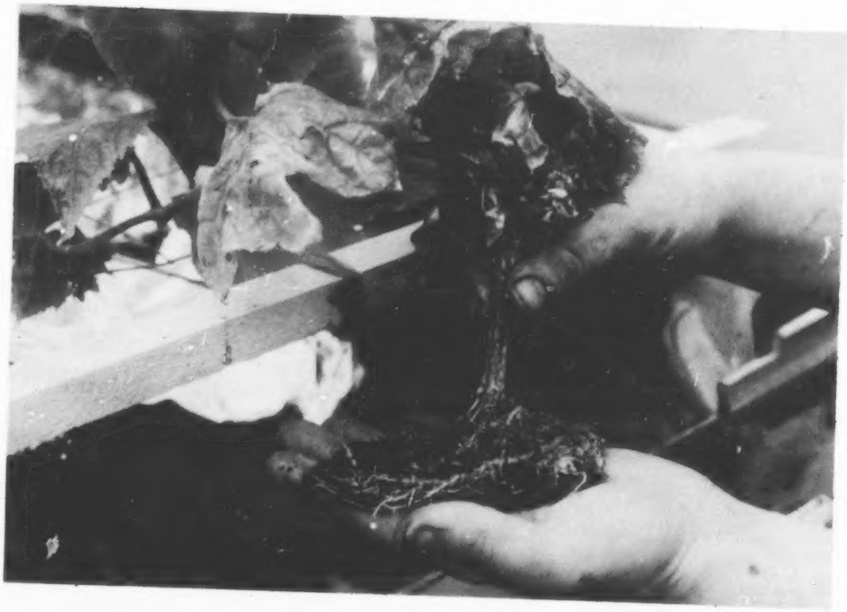

Figure 7.76. Poor root development of cucumber after a month in the NFT unit in the Hanover greenhouse.

Petunias flowered but never grew in height or put out new roots. Leaves yellowed and dropped, and roots eventually rotted away.

Plant Order in the NFT Sewage System--Plant species were placed in the NFT units in the order in which they were judged most suited: first, plants able to withstand high solids sedimentation and anaerobic root zones; second, plants capable of rapid nutrient uptake and high biomass production; and third, plants capable of flourishing on low nutrient concentrations. The initial setup of the multispecies unit is shown in Figure 7.77. Cattails and bulrushes were in the first 6.1 meter section followed by other wetlands plants considered hardy enough to survive the adverse conditions. Because little was known of the other species' responses to sewage, they were arranged in the remaining 24.4 meter section on the basis of their expected nutrient uptake. As more species became available, they were entered into available spaces judged best suited to them.

The specific placement of plants in the units did have a significant affect on the performance of some species. Roses grew well when they were placed in a location 30 to 35 meters downstream of the influent but fared poorly when placed between 10 and 12 meters. This later section failed to produce buds and grew slowly. Similarly, tomatoes grew better between 35 and 36 meters than between 20 and 24 meters.

Some species appeared to grow well regardless of placement. Napier grass thrived at the 35 to 36 meter location and also at the 12 to 13 meter section. In fact, napier grass cuttings were propagated in the sewage film between 13 and 15 meters. Millet also grew well in considerably different locations, first at 29 to 30 meters and later at 10 to 12 meters. In the main testing unit, phragmites did not perform well when it was in the first 12 meters of the unit. This part of the unit had only a slight slope and usually contained standing sewage. Phragmites roots were clogged with solids and were not growing well. For testing of the second condition, the phragmites were moved to the 12 to 24 meter position which was further downstream and had a greater slope. The phragmites roots performed well there (as did the cattails and bulrush which replaced it in the first 12 meters).

From these observations one could conclude that more species could survive further from the influent than closer to it. The D.O. profile of this unit generally supports this. The ability of some plants to grow at various locations indicates that the organic buildup is not an impediment to plants in general, but it may have a gradient effect on some species.

One question that was not answered was whether plants which thrived at the influent (cattails and bulrush) could survive in lower reaches where conditions were more favorable to most plants.

Plants Removed for Potting--Toward the end of the experimental phase, flower species were removed from the multispecies unit and potted. This was done to see whether placing them in a soil medium would improve their vigor or, if they were growing well, to find out if they could be potted for transport. Six flower species were selected. Of these, carnations,

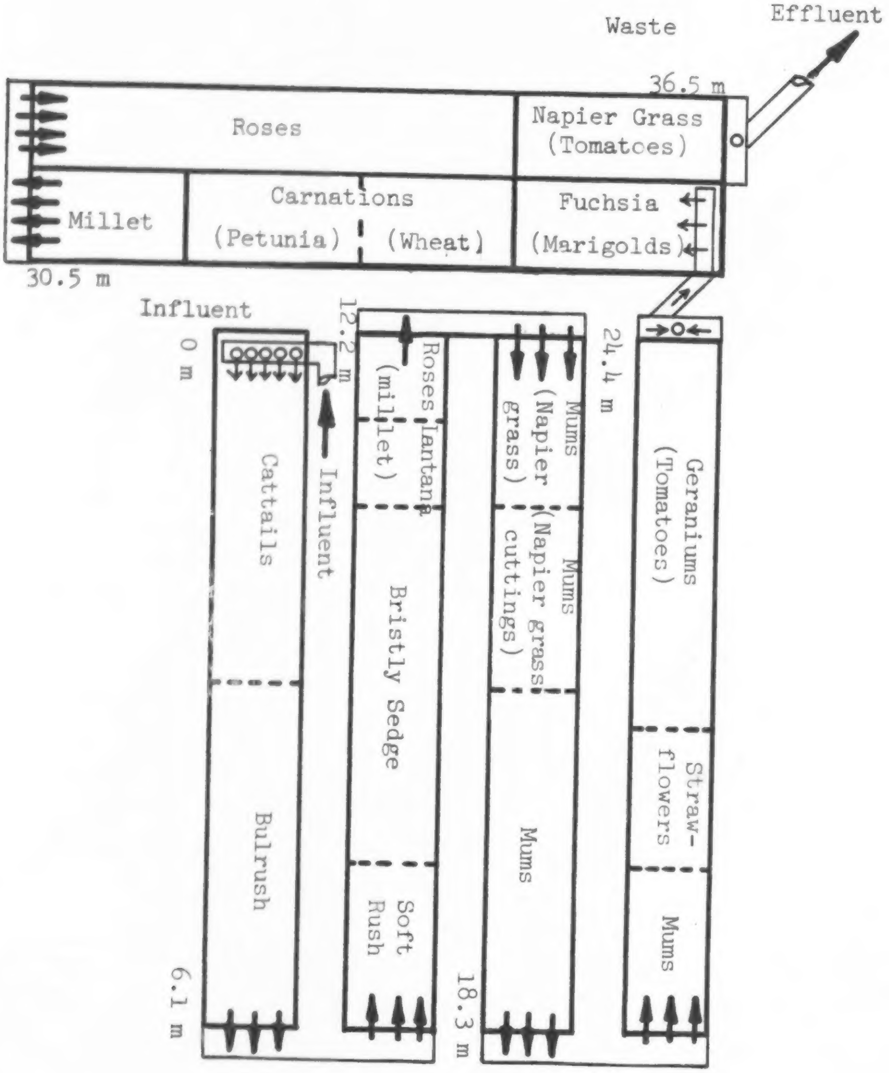

Figure 7.77. Schematic diagram of second system in Hanover greenhouse showing locations of plants relative to sewage flow. Distances shown are lengths from sewage influent. Plants in parentheses were introduced later in the experimental program.

chrysanthemums, geraniums and lantana improved their vigor after repotting, looked much healthier and increased their growth rate. The two species which showed no significant improvement after potting were roses and fuchsia.

F.3. Diagnosing and Treating Plant Growth Problems

Because reed canary grass was the most frequently used test species, most experience was obtained in diagnosing and treating problems associated with the growth of this species. In the Brace house the plant was grown continuously for two years, during which time it suffered several infestations. The major pathologies and treatments are shown in Table 7.19. Aphids flourished periodically, probably because of the absence of naturally occurring predators. Fungus infestations in turn developed on the sugary "honey dew" secretions of the aphids. There developed a large population of spiders, however, which heavily fed upon the aphids and flies (Psychoda), which abounded in the greenhouse.

TABLE 7.19. REED CANARY GRASS PATHOLOGIES AND TREATMENTS

Problem	Treatment	Major Results	Minor Results
Algae clogging seedling roots and increasing pH	0.2 mg/l $CuSO_4$ in recirculated solution	Algae growth cut back; grass outgrew algae	None; solution replaced after 3 days
Aphid infestations and secondary fungal attack	Chemical pesticides	Aphids wiped out; fungus infection reduced	Grass matted down by heavy spray
Aphid infestation	Biological treatment by lady beetle introduction	Aphids controlled; few adult bettles noted; control may also be due to spiders or parasites	None
Fungal infection (Pythium sp.)	Specific fungicides Subdue and Bayleton used	Drought symptoms remedied	Testing suspended during treatment; effects on microflora unknown but may be major
Fe deficiency	Sequestrene chelated Fe added	Yellow appearance disappeared	Plants less susceptible to fungus attack

The atmosphere in the Brace house had a high relative humidity due to the constant operation of the NFT units. This high humidity was relieved only

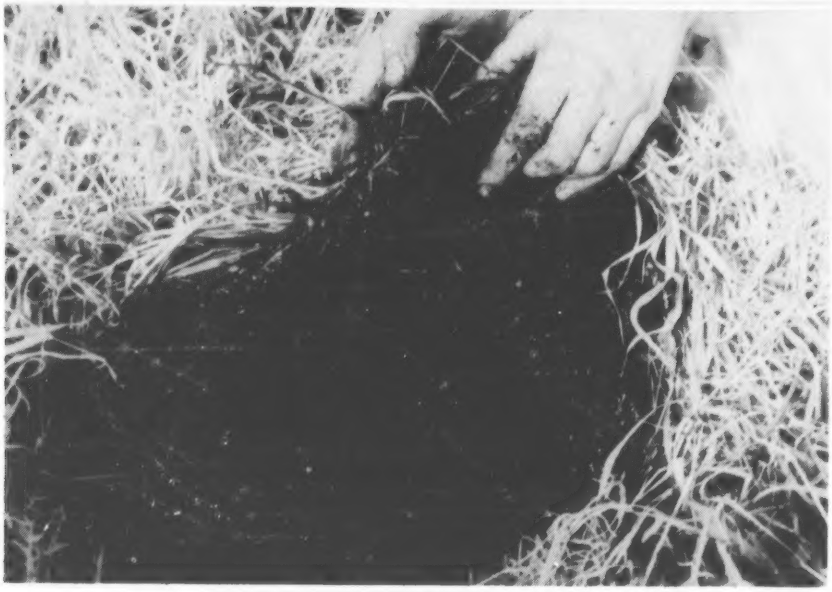

Figure 7.78. Black root zone below dead reed canary grass.

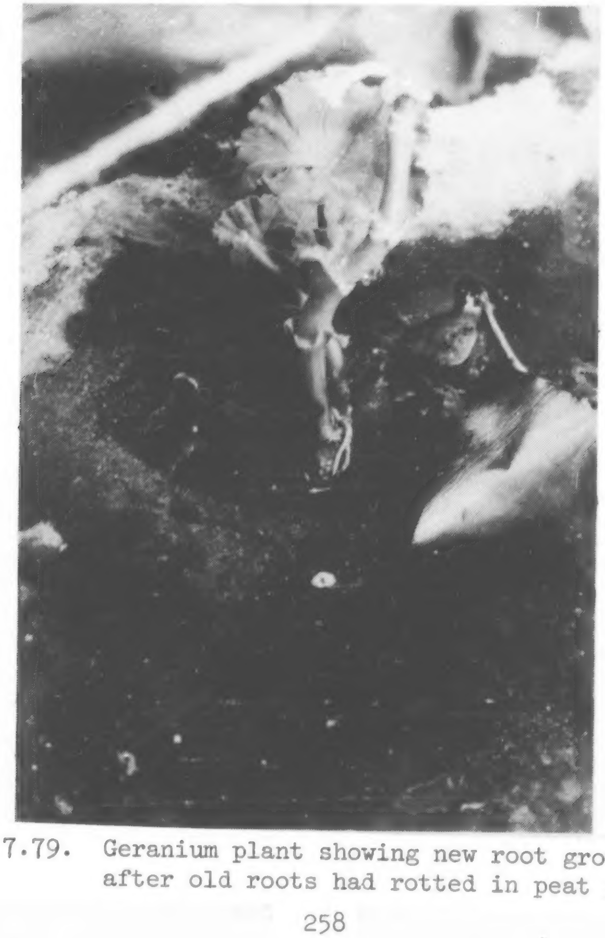

Figure 7.79. Geranium plant showing new root growth after old roots had rotted in peat pot.

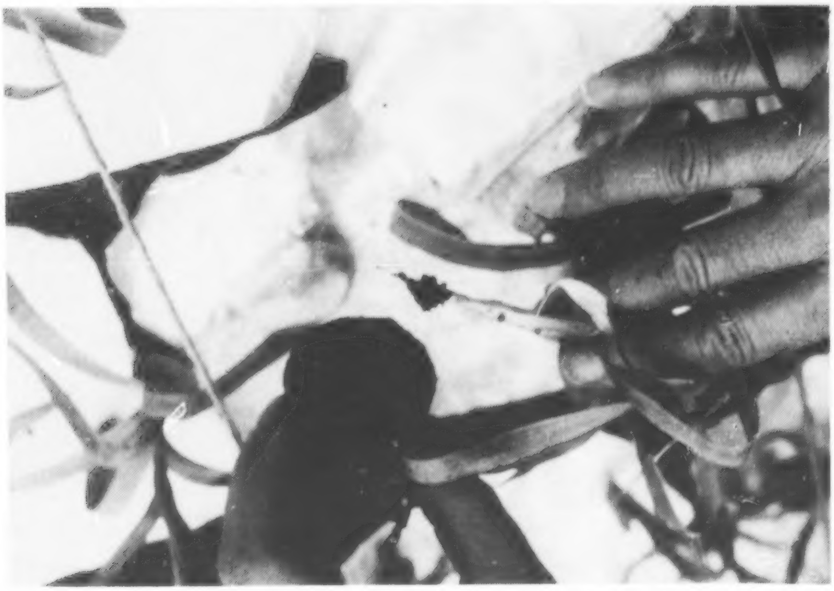

Figure 7.80. Chrysanthemum and peat pot showing absence of roots due to root death.

by ventilation used for cooling. High temperatures coupled with this high humidity provided excellent conditions for fungus development. Infection of a Pythium species occurred several times. This disease caused the death of the more mature grass leaves. These infestations appeared to be prevalent during periods when the grass was stressed. Aphids were commonly noted on grass leaves when the units were operated at high hydraulic loading rates which resulted in anaerobic deposits among the roots. Pythium infection was noted during a period of nutrient deficiency in the feed solution.

In the sewage loaded system the canary grass grew well until higher loading rates (20 centimeters per day) were tested. Solids then accumulated among the roots and produced an anaerobic black colored mass (see Figure 7.78). Grass roots died and plants grew poorly until the deposits were removed by flushing with fresh water. The grass soon thereafter recovered.

Other plants suffered similar infestations. Weakened plants were susceptible to pest attack and became hosts to the rapidly reproducing disease organism. Before long the spread of the disease to nearby healthy plants would be noted. Growing several species in the same greenhouse requires close observation and timely action to control pests. In commercial greenhouses this problem is overcome by limiting a particular greenhouse to a single species, which allows the climate to be tailored to the plant.

General root death affected many species when they were grown in sewage. These species included geraniums, cucumbers, chrysanthemums, fuchsias, carnations, petunias, tomatoes and lantana. Figure 7.79 shows a geranium partially recovering from root death, and Figure 7.80 shows a similar condition in a chrysanthemum. It was hypothesized that some of this root death was due to waterlogging by the peat pots. Removal of the peat material from the roots, however, resulted in no improvement. Along with the root death, fungus gnat larvae appeared in the sewage test units and grew to large populations (see Figure 7.81). A solution of diazanon was used to soak the root zone of all the plants downstream of any known occurrence of the fungus gnats. Some improvement was noted in plants following this treatment and the removal of peat pots, but the fungus gnats were not eliminated from the system.

To ensure that atmospheric gases had maximal exposure to the sewage, the placement of black plastic, used to inhibit algae growth, was elevated in the units so that it was not in contact with the sewage.

White flies infested cucumbers, fuchsias, tomatoes and lantana. These insects often pose a serious problem in commercial production of these crops. They were treated with Resmethrin spray and controlled, but not eradicated. Periodic treatments were necessary.

Aphids infested many plants but were particularly severe on chrysanthemums, bulrushes and cattails. In the sewage system, the general treatment for aphids was fumigation with a nicotine bomb. This treatment was effective in the short term, but needed to be repeated periodically.

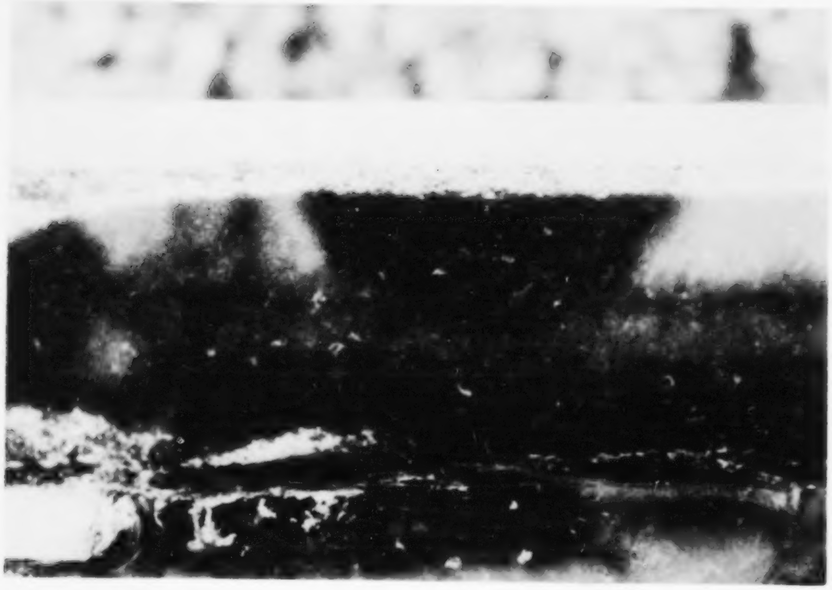

Figure 7.81. Larval gnats in connecting gutter between trays at the Hanover greenhouse.

Spider mites first infected roses and were treated with rose dust. At their peak they infested many plants such as cattails, cucumbers, blackberries, bulrush, etc. Pentac was used as the general spider mite treatment. Again the treatment had to be repeated at regular intervals.

G. TOXIC CONSTITUENT CONSIDERATIONS--CADMIUM AND TOXIC ORGANICS (VOLATILE AND NONVOLATILE)

The data presented earlier for the composition of canary grass species in Tables 7.10 through 7.14 and Figure 7.82 showing the example decrease in cadmium are useful in describing the fate of these elements in wastewater. Most of the cadmium data and the application rates that were used to various systems are shown in Table 7.20. This table confirms the rapid uptake of cadmium. The influent concentrations of 0.1 to 0.3 mg/ℓ represent a wastewater that is relatively contaminated with an industrial waste that generates significant quantities of cadmium. These values decreased significantly in the effluent down to low values of around 0.01 and 0.02 and 0.04 in most cases. Domestic sewage often contains values of .01 mg/ℓ cadmium. Example cadmium removal rates are shown in Figure 7.82.

The data shown in Table 7.11 and 7.12 indicate that the canary grass had significant concentrations of cadmium in the plant tissue. An effort to illustrate the mass flow of cadmium through the system is shown in Table 7.20. The cadmium uptake in the plants appeared to be an insignificant portion of that applied. This indicates that since in many cases most of the cadmium was removed, the larger majority of the cadmium is assimilated and held in the root zone.

Due to the high concentration of microbes (entrapped mass greater than 1,000 g/m^2) in the large root surface area, it was hypothesized that the NFT system should have some active pollutant removal mechanisms for some of the toxic organics. Experiments were conducted by adding small amounts of background toxic organics by Jenkins of the CRREL staff. A summary of the fate of the volatile and nonvolatile organics is shown in Table 7.21. This information indicates that the 36 meter long units were effective in removing most of the applied volatile organics and nonvolatile organics, excepting for diethylphthalate. In all cases the PCB's that were added to the system were removed by greater than 90 percent even at high concentrations. This information suggests that the NFT roughing treatment system could also be significant in removing the toxic organics that will be contained in many wastewaters.

H. COMPARISON OF SYNTHETIC AND DOMESTIC SEWAGE IN NFT SYSTEMS

The general approach of this study was to attempt to operate synthetic wastewater under comparable loading conditions as the tests with the domestic sewage. The goal was to show that the results that were obtained with a synthetic wastewater could be extrapolated to sewage so that future testing could be simplified at small scale with a synthetic wastewater. The data shown in Tables 6.11 (characteristics of influent synthetic and domestic sewage) and Figure 7.83 indicate that there was a good correlation between a number of the variables in synthetic wastewater and domestic

TABLE 7.20. FATE OF CADMIUM IN NFT PILOT SYSTEMS AT CORNELL

Dates	Area Loading Cm/d	System Size m^2	Number of Units	Cd Applied mg/m^2-d	Cd Effluent mg/m^2-d	Cd in plants mg/m^2-d	Cd in RCG mg/m^2-d (Univ. No.)	Cd in Phrag. mg/m^2-d (Univ. No.)	Cd in Cukes mg/m^2-d (Univ. No.)	Cd in Cattail-Bulrush mg/m^2-d (Univ. No.)	Cd Control RCG mg/m^2-d
3/18/80 - 5/11/80	5.1	9.3	1	16.80	2.55	$3.42x10^{-3}$ $(\pm 2.10x10^{-3})$	$3.42x10^{-3}$ (1)	----	----	----	$2/14x10^{-3}$
5/12/80 - 6/17/80	10.2	9.3	1	21.42	6.12	$3.53x10^{-3}$ $(\pm 2.10x10^{-3})$	$3.53x10^{-3}$ (1)	----	----	----	$2.63x10^{-3}$
6/18/80 - 7/ 3/80	5.1	9.3	1	7.65	3.06	0.36 $(\pm 0.36x10^{-3})$	$0.36x10^{-3}$ (1)	----	----	----	$1.02x10^{-3}$
7/ 4/80 - 9/ 8/80	20.3	9.3	1	30.45	18.27	$2.86x10^{-3}$ $(\pm 2.83x10^{-3})$	$2.86x10^{-3}$ (1)	----	----	----	$0.58x10^{-3}$
9/ 9/80 - 10/15/80	10.2	18.6	2	19.38	6.12	$7.46x10^{-3}$ $(\pm 6.57x10^{-3})$	$7.46x10^{-3}$ (1&2)	----	----	----	$1.20x10^{-3}$
10/16/80 - 10/31/80	20.3	18.6	2	50.75	22.33	$4.73x10^{-3}$ $(\pm 5.57x10^{-3})$	$4.73x10^{-3}$ (1&2)	----	----	----	$1.18x10^{-3}$
2/13/81 - 3/14/81	6.9	27.9	3	2.07	0.21	----	0.01 (3)	----	----	----	$4.6x10^{-4}$
4/16/81 - 5/10/81	10.2	27.9	3	18.36	5.10	----	$4.4x10^{-3}$ (3)	----	----	----	$1.7x10^{-3}$
5/11/81 - 6/10/81	20.3	27.9	3	12.18	4.12	----	----	----	----	----	----

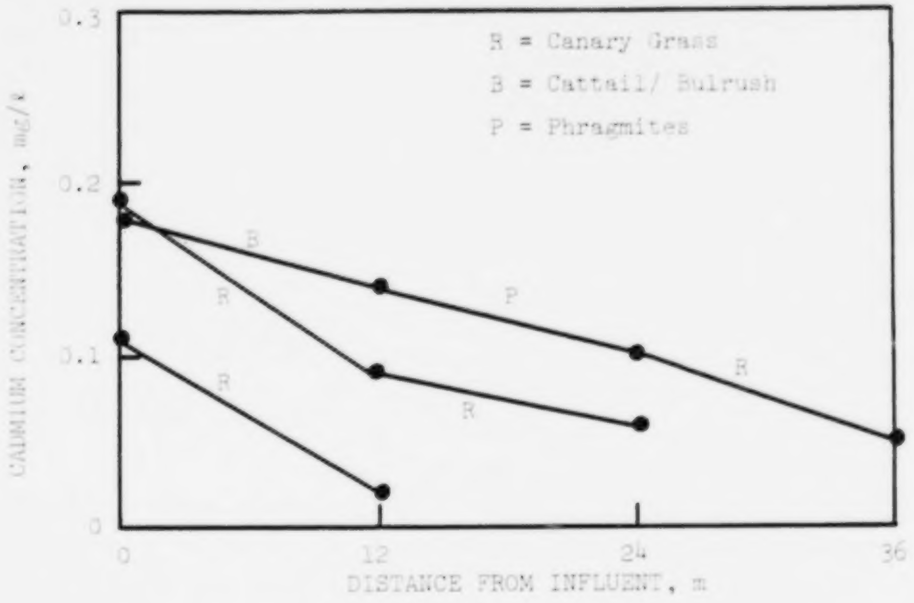

Figure 7.82. Cadmium concentrations at various points in three different length systems, the longest of which contained several species. All curves from 10.2 cm/d loading conditions.

TABLE 7.21. TRACE ORGANIC CONCENTRATIONS IN SEWAGE IN THE HANOVER NFT SYSTEM.
(Values in ppb)

Volatile Trace Organics

	CHLOROFORM				TETRACHLOROETHYLENE				BENZENE				TOLUENE				TRICHLOROETHYLENE				XYLENE			
Date	Applied	Effluent from			Applied	Effluent from			Applied	Effluent from			Applied	Effluent from			Applied	Effluent from			Applied	Effluent from		
		First	Second	Third		First	Second	Third		First	Second	Third		First	Second	Third		First	Second	Third		First	Second	Third
3/10/81[1]	0 %	63 %	94 %	100 %	0 %	61 %	97 %	99 %	0 %	76 %	---	---	0 %	57 %	68 %	96 %								
3/12/81	65.9	28.0	6.53	1.17	12.2	3.65	.533	.118	29.9	2.18	.219	---	44.3	10.7	4.45	.137								
4/15/81	37.2	9.86	5.05	1.84	9.83	3.14	.880	.355					19.5	5.77	1.41	---	169	58.4	20.5	7.1	29.7	16.2	4.77	2.11
4/24/81	10.6	4.92	2.14	1.18	.529	.276	.154	.077	1.44	.425	.148	.081	40.8	14.2	4.87	1.41	1.82	1.03	0.61	0.26	67.7	25.2	9.64	2.87

Nonvolatile Trace Organics

	BROMOFORM				M-NITROTOLUENE				DIETHYLPHTHALATE				PCB 1242			
	Applied	Effluent from			Applied	Effluent from			Applied	Effluent from			Applied	Effluent from		
		First	Second	Third		First	Second	Third		First	Second	Third		First	Second	Third
3/18/81	47.4	1.87	0.22	0.23	58.4	3.41	0.42	0.17	82.1	77.6	43.6	29.6	39.6	10.0	6.3	3.9
3/25/81	45.8	3.4	0.59	0.15	39.2	5.2	0.26	$<d^2$	81.8	64.6	59.7	19.9	17.6	4.5	1.7	1.1
4/29/81	44.8	8.2	5.4	1.4	10.2	8.0	3.2	0.5	101	77.2	76.2	38.6	21.8	3.0	2.0	0.45
5/ 6/81	611	122	52	16	228	49	20	29	449	239	186	58	738	<40	<40	<40

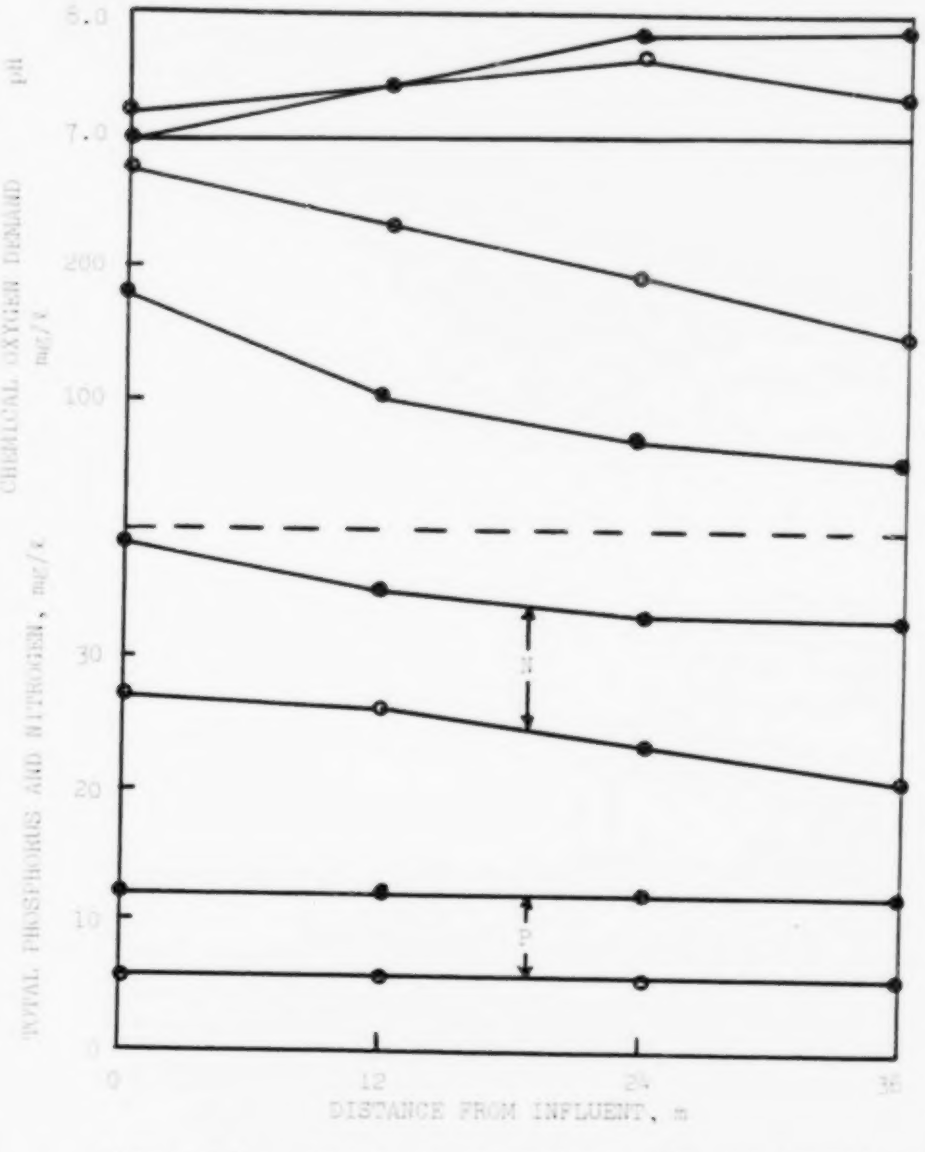

Figure 7.83. Comparison of synthetic (●) and domestic (○) sewage variables in 27.9 m^2 units operated at an area loading rate of 10.2 cm/d.

sewage. Figure 7.84 compares the removal of total chemical oxygen demand in domestic and synthetic wastewater as a function of application of flow rate in the system. This indicates that at many of the loading rates the removals that were observed were similar. Tables 7.22 and 7.23 show a comparison of the mass removals of various pollutants for the two different substrates studied. In general, the rates observed for the various parameters where the loading rates were comparable were in the same order of magnitude. This information should be useful in enabling the system to be defined both in this study and others for the application of typical wastewater to the NFT system.

The average performance of the two systems at the varying loading conditions is also summarized in Tables 7.22 and 7.23. This information summarizes the large amount of data that was developed for the pilot application and as presented earlier under the various pollutants.

I. DEVELOPMENT OF PREDICTIVE RELATIONSHIPS

Two approaches were examined to predict effluent quality from NFT units applied to wastewater treatment. First is a correlation of loading rate relationships to the effluent quality. This approach included an attempt to correlate plant yield information to removal efficiencies of various pollutants. The earlier figures correlating removal rates are useful in estimating area requirements for treatment systems. The second approach was to apply simple removal kinetics to the information to define the time required for varying influent concentrations to achieve a given level of efficiency.

A comparison and summary of the removal rates presented earlier are given in Table 7.24 as examples from which the size of an NFT system might be predicted. Some of the limitations of this information include restricted nutrient uptake and yield due to the dual application of suspended solids and BOD. At no time was a high quality effluent from an optimized treatment system fed to healthy, high-yielding plants to test the nutrient removal capacity.

A kinetic examination of the data was performed using the assumption that the flow in these units approached plug flow and that the removal of the pollutants was first order and described by the following equation:

$$S_e = S_o \cdot e^{-kt} \qquad (7.4)$$

where S_e = effluent concentration

S_o = influent concentration

k = removal rate coefficient

t = time of exposure of the reaction or the hydraulic retention time in the unit

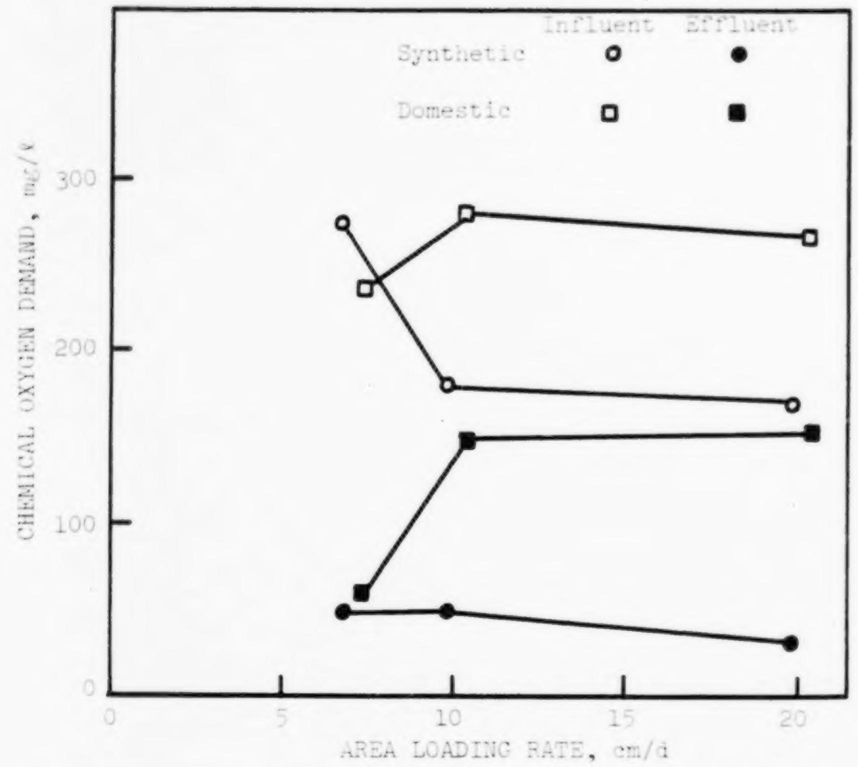

Figure 7.84. Comparison of chemical oxygen demand reductions in domestic and synthetic sewage at various loading rates in 27.9 m^2 units.

TABLE 7.22. SYSTEM PERFORMANCE SUMMARY OF PILOT SCALE SYSTEMS USING SYNTHETIC SEWAGE.

Target Area L.R. cm/d	COD			Soluble COD			Total Phosphorus			Soluble Phosphorus			Total Nitrogen			Soluble Nitrogen			Cadmium			Soluble Cadmium		
	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%
10.2	412	244	59	412	245	60	16.9	0.2	1	17.7	1.1	6	38.7	6.7	17	38.8	9.8	25	.112	.092	82			
10.2	318	150	47	382	203	53	10.9	1.2	11	13.5	3.9	29	42.2	12.5	30	38.3	9.0	24	.112	.102	91			
10.2	377	104	28	392	129	33	16.0	1.2	8	16.2	1.1	7	34.2	Increase	—	39.2	8.6	22	.061	.041	67			
10.2	407	257	63	382	234	61	14.3	2.2	16	13.7	1.4	10	36.3	6.5	18	38.7	10.7	28						
5.1	215	187	87	213	182	85	7.2	0.7	10	7.2	0.5	6	19.0	4.2	22	19.3	4.6	24	.168	.143	85			
10.2	280	241	86	278	244	88	15.1	1.2	8	14.1	0	0	41.9	9.6	23	41.4	8.0	19	.214	.163	76			
5.1	133	101	76	128	103	80	7.4	3.8	52	7.2	3.8	53	18.8	6.0	32	18.3	7.3	40	.076	.046	60			
20.3	392	265	68	376	250	66	29.3	Increase	—	29.5	Increase	—	71.1	15.6	22	68.5	13.2	19	.305	.122	40			
10.2	210	191	91	101	87	86	9.9	Increase	—	13.5	3.3	24	34.1	19.5	57	37.0	12.8	35	.193	.132	68			
20.3	395	342	87	391	338	86	27.1	0.2	1	27.7	1.0	4	35.8	Increase	—	38.3	Increase	—	.509	.285	56			
6.9	187	154	82	194	170	87	11.3	0.9	8	10.7	0.3	3	26.5	5.9	22	25.3	5.6	22	.020	0	0	.014	.007	50
10.2	185	137	74	173	131	76	13.4	2.3	17	12.3	0.9	7	39.7	6.6	17	37.6	6.0	16	.183	.132	72	.173	.142	82
20.3	384	283	81	375	310	83	12.0	0.4	3	12.2	1.2	10	36.2	12.6	35	34.8	12.8	37	.122	.081	67	.122	.102	83
40.6	972	414	43	903	461	51	50.1	Increase	—	45.6	Increase	—	140.8	8.1	6	132.3	2.0	2						
6.9	144	46	32	151	101	67	6.2	Increase	—	5.7	Increase	—	13.3	Increase	—	11.3	Increase	—						
10.2	460	330	72	390	311	80	16.9	0.1	1	15.0	Increase	—	57.1	4.8	8	58.6	7.8	13						

TABLE 7.23. SYSTEM PERFORMANCE OF PILOT SCALE SYSTEMS USING DOMESTIC SEWAGE

Target Area L.R.	BOD			TOC			COD			Soluble COD			Total Nitrogen			Total Phosphorus			Suspended Solids			Volatile Suspended Solids			Soluble BOD		
cm/d	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%	Mass L.R. kg/ha-d	Removal kg/ha-d	%
5.1																											
4.0																											
10.2	172	129	75	132	97	73													117	96	82	54	41	76			
10.2	109	67	61	75									44.5	2.8	6	7.22	0.38	5	73	45	62	65	41	63			
10.2	103	69	67	84	47	56							41.2	6.5	16	6.31	1.22	19	68	40	59	46	33	72			
5.1	62	44	71	42	26	62							20.2	5.7	28	3.77	1.21	32	47	36	77	35	27	77			
20.3													67.9	12.7	19	12.96	1.77	14	106	153	74	180	145	83			
5.1	58	48	83	48	35	73							17.5	3.1	18	3.05	0.71	23	46	31	67	29	20	69			
10.2	101	80	79	84	43	51							27.3	4.6	17	4.84	0.39	8	110	78	71	108	95	88			
20.3	133	118	89																175	164	94	174	167	96			
6.9	67	61	91	49	35	72	133	99	74	94	62	66	13.0	3.3	25	2.97	0.67	23	20	17	85	24	22	92	44	38	86
10.2	182	134	74	101	59	58	372	190	51	272	113	42	36.4	11.1	30	7.62	1.67	22	57	48	84	50	42	84	120	78	65
20.3	272	166	61	100	51	51	556	247	44	395	144	36	44.4	6.9	16	12.09	1.12	9	98	66	67	87	56	64	150	74	47

TABLE 7.24. COMPARISON OF MEAN MASS REMOVALS FROM SYNTHETIC AND DOMESTIC SEWAGE IN PILOT SCALE SYSTEMS. (kg/m^2-d)

	Domestic Sewage			Synthetic Sewage			
Average Flow (ℓ/d)	1563	3804	5773	1913	2834	5668	11336
Target Loading (cm/d)	7	10	20	7	10	20	40
Total BOD	.0062	.0125	.0131	--	--	--	--
Soluble BOD	.0042	.0078	.0064	--	--	--	--
Total COD	.0105	.0181	.0197	.0134	.0137	.0295	.0496
Soluble COD	.0065	.0104	.0104	.0153	.0138	.0315	.0522
Total TOC	.0038	.0056	.0048	--	--	--	--
Total SS	.0025	.0047	.0064	+	+	0	+
Volatile SS	.0022	.0040	.0054	1.4×10^{-4}	+	0	+
Total N	5.3×10^{-4}	8.3×10^{-4}	3.9×10^{-4}	6×10^{-5}	7×10^{-5}	1.4×10^{-4}	+
Total P	9×10^{-5}	1.0×10^{-4}	2×10^{-5}	.0001	.0002	8×10^{-5}	+
CD	--	--	--	1×10^{-6}	1×10^{-5}	1×10^{-5}	2×10^{-5}

- = Not determined

+ = Increase in concentration through system

By plotting the removal efficiency versus the hydraulic retention time in the system it is possible to obtain an empirical determination of k, the substrate removal coefficient. If the data follow a straight line on a semi-log plot, it also confirms that the reaction rate is driven by the substrate concentration in the reactor and that it is a first order relationship. Departures or scatter of the data reflect the fact that the system is being tested in a substrate-limited zone, that the reaction is not first order, or that the system is a significant departure from a plug flow and that mixing and short-circuiting occurred.

Example plots of rate determinations for BOD, suspended and volatile solids, nitrogen, and phosphorus for domestic sewage are shown in Figures 7.85 through 7.89. Similar plots for COD, nitrogen and phosphorus removal from synthetic sewage are shown in Figures 7.90 through 9.92. The substrate removal rate coefficient as determined from this information is summarized in Table 7.25. This information, although quite variable, tends to indicate that the removals are first order for most of these systems. Because of the variability of the data, this approach has a limited value in the design of this system. The application of this information to sizing the units will be presented in the next section.

TABLE 7.25. SUMMARY OF SUBSTRATE REMOVAL COEFFICIENTS AS DETERMINED FROM ASSUMED FIRST ORDER KINETIC ESTIMATES FOR CANARY GRASS SYSTEMS

Sewage Type	Variable	k
Domestic	BOD	-0.0015
	TSS	-0.0096
	VSS	-0.010
	N	-0.0016
	P	-0.0016
Synthetic	COD	-0.0038
	N	-0.0001
	P	-0.0008

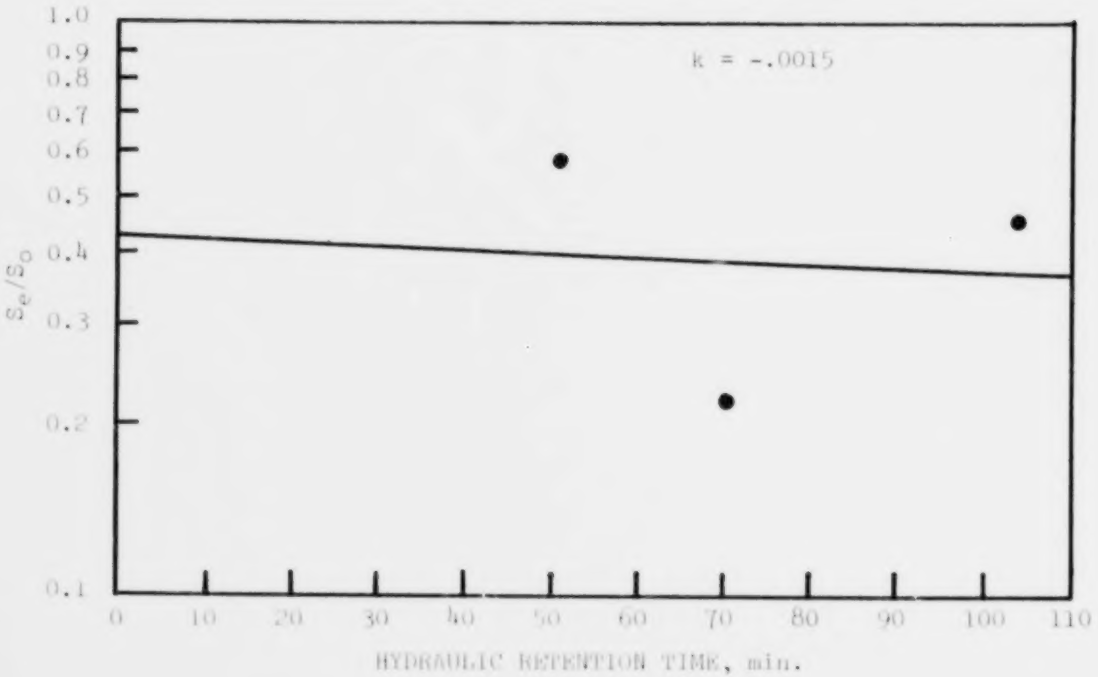

Figure 7.85. Rate determination plot for BOD removal from domestic sewage by a canary grass system.

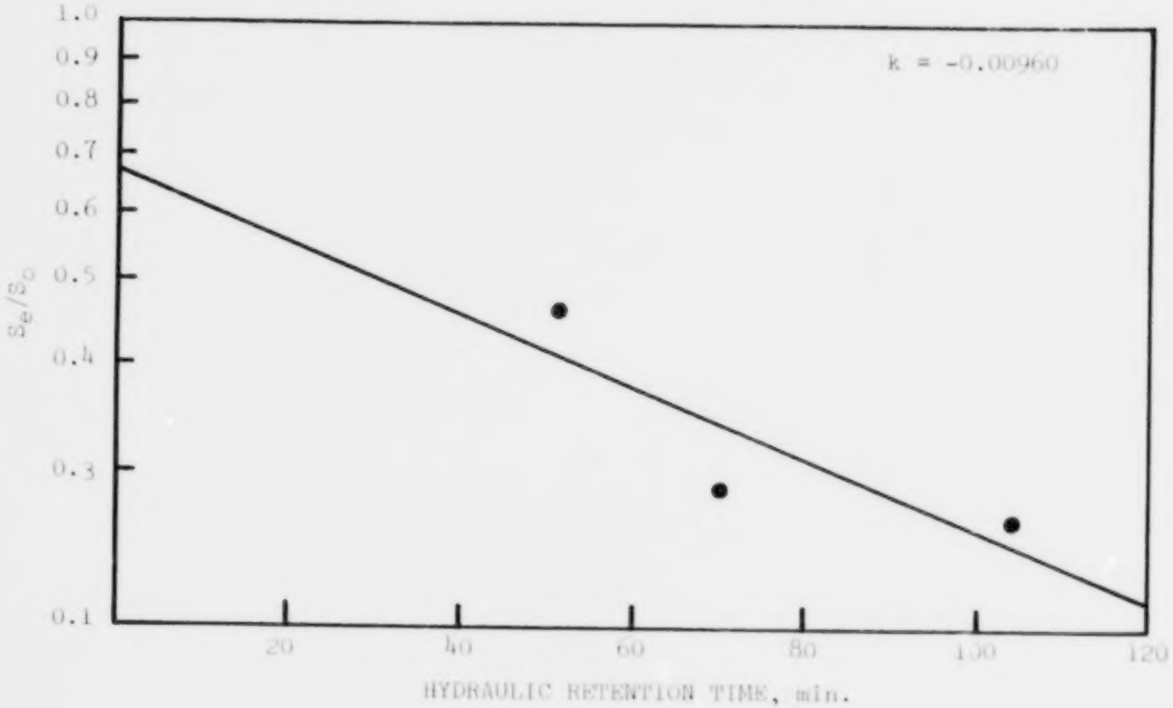

Figure 7.86. Rate determination plot for suspended solids removal from domestic sewage by a canary grass system.

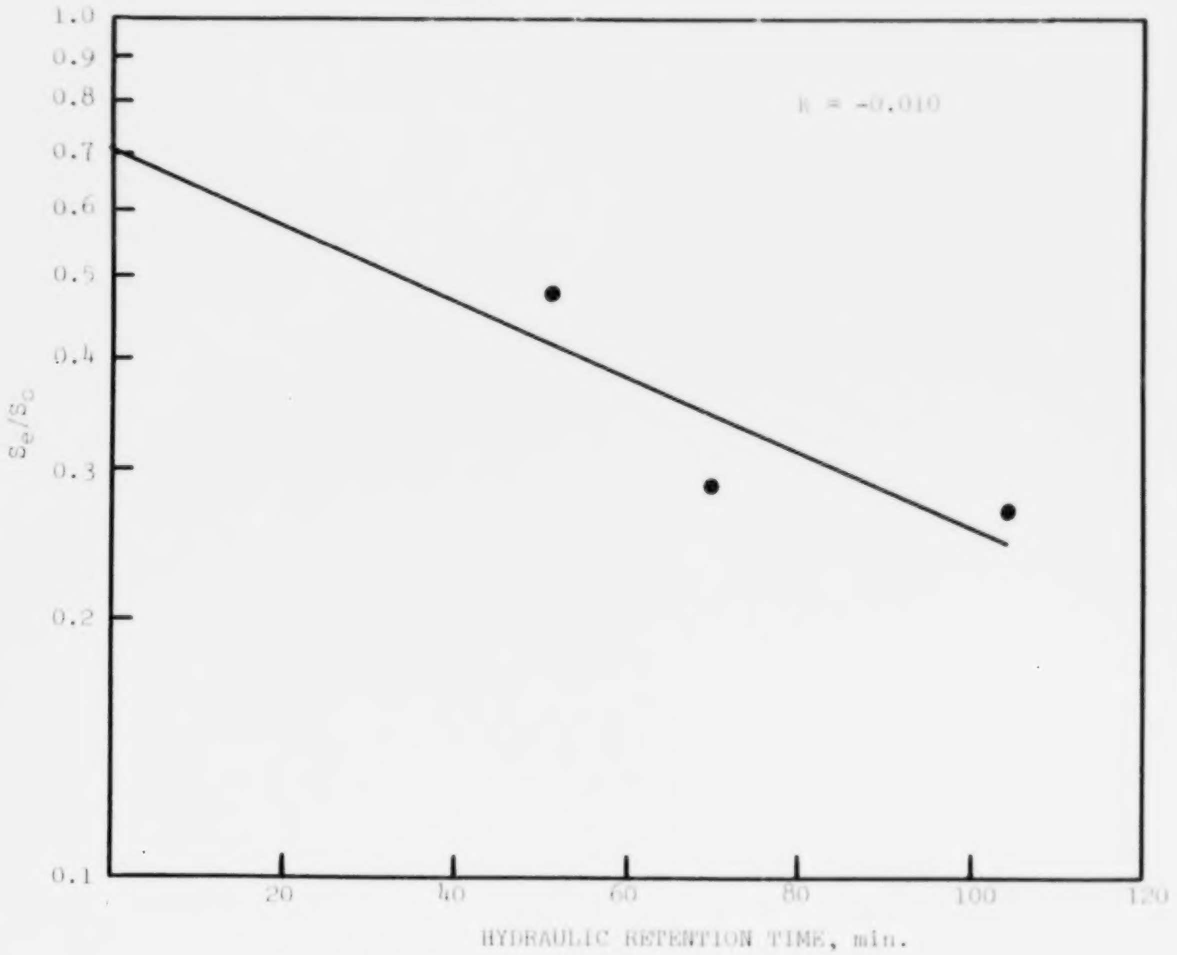

Figure 7.87. Rate determination plot for volatile suspended solids removal from domestic sewage by a canary grass system.

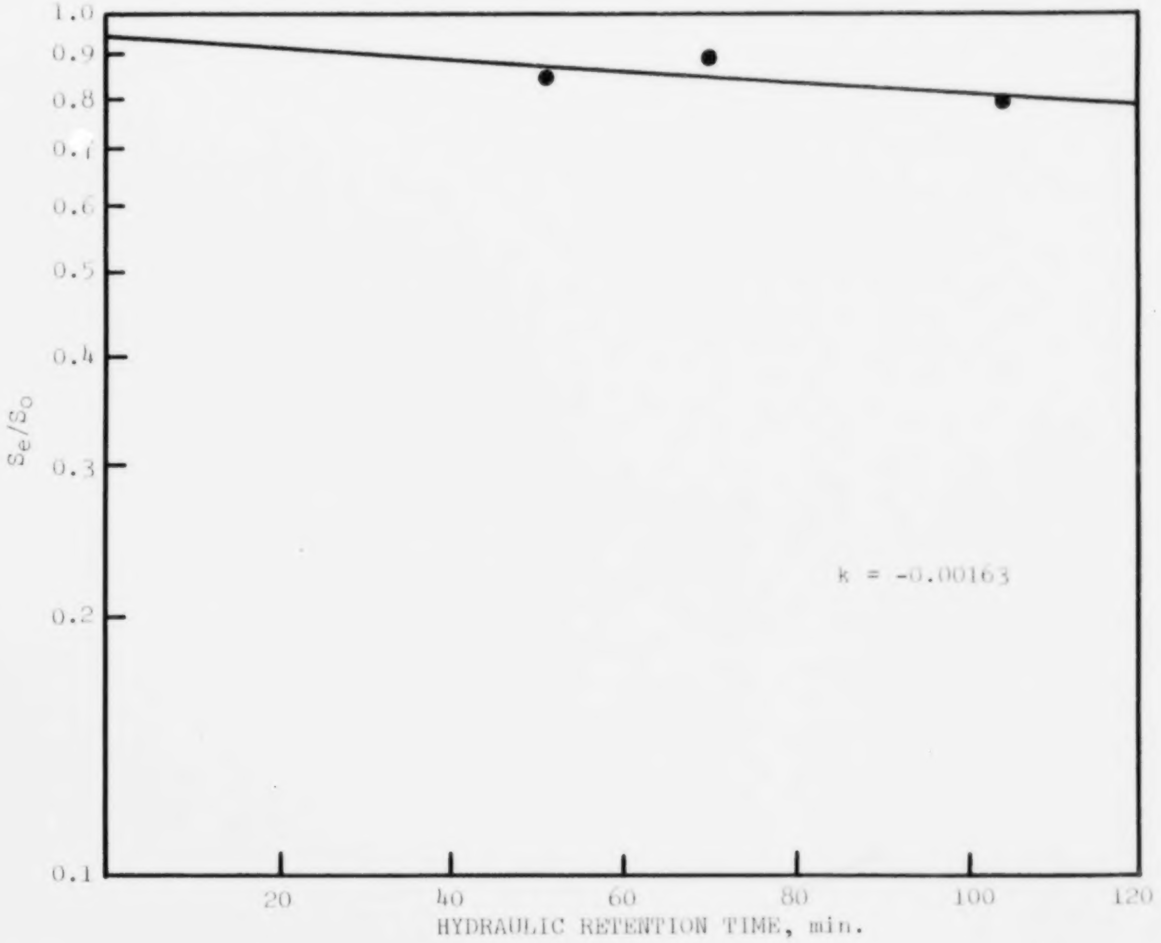

Figure 7.88. Rate determination plot for total nitrogen removal from domestic sewage by a canary grass system.

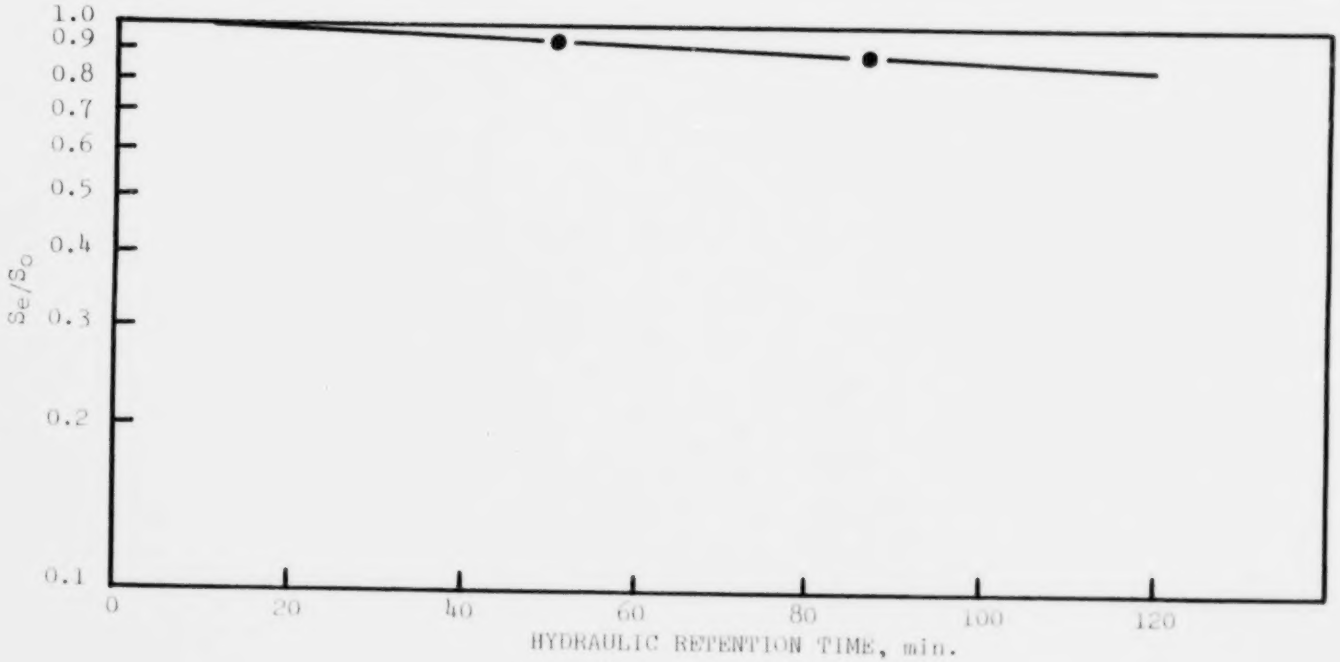

Figure 7.89. Rate determination plot for total phosphorus removal from domestic sewage by a canary grass system.

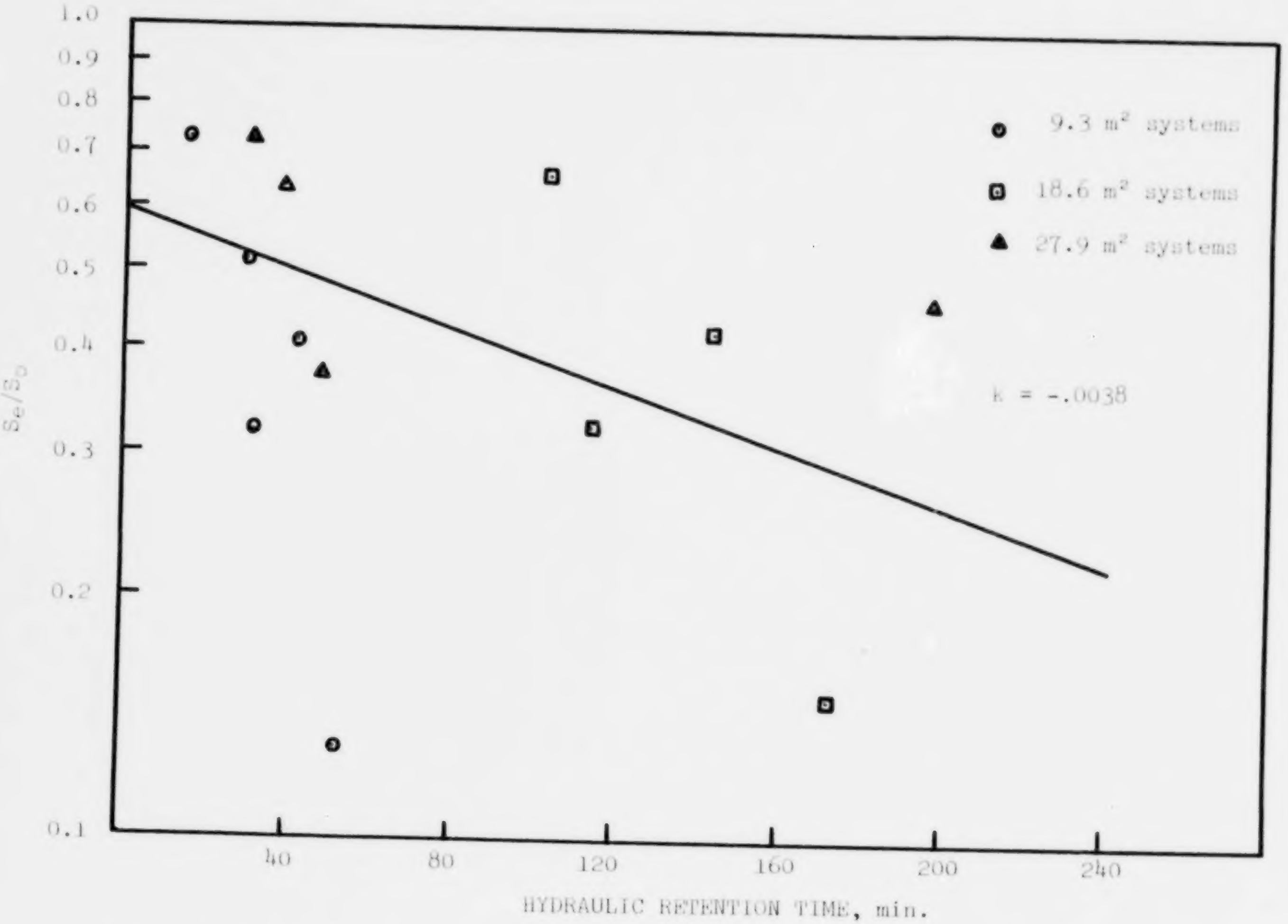

Figure 7.90. Rate determination plot for COD removal from synthetic sewage by canary grass units in different size systems.

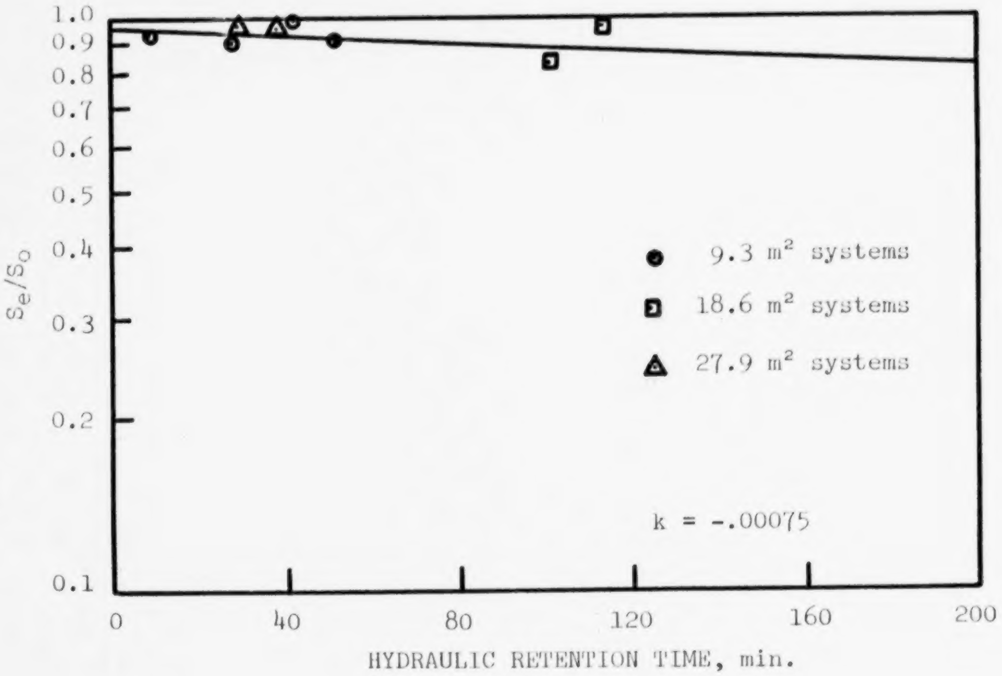

Figure 7.91. Rate determination plot for phosphorus removal from synthetic sewage by canary grass units in different size units.

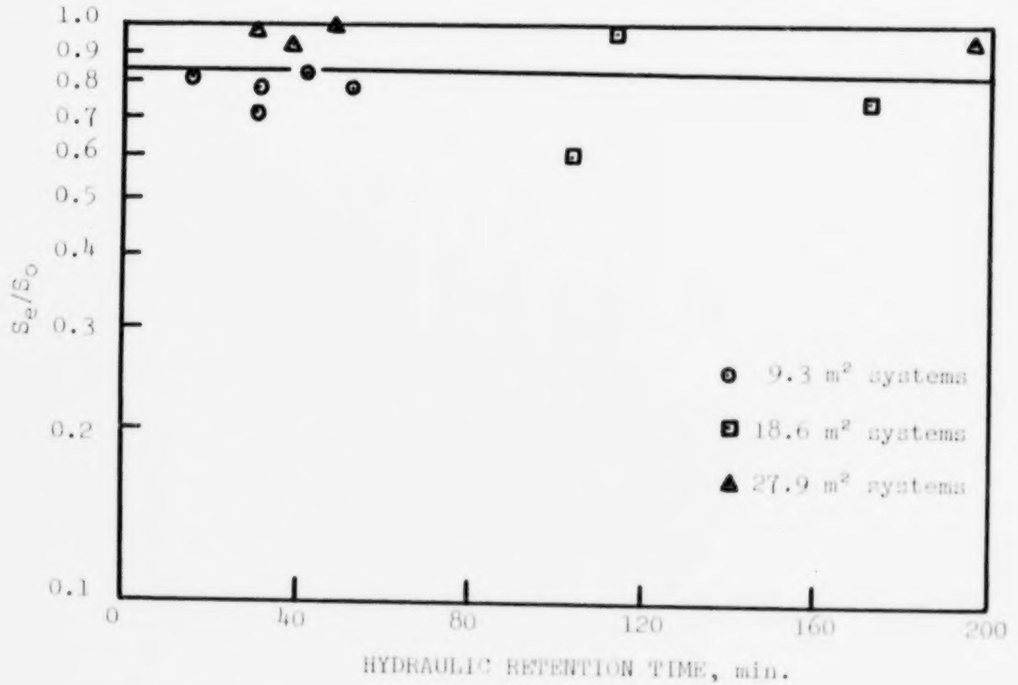

Figure 7.92. Rate determination for total nitrogen removal from synthetic sewage in canary grass units of different areas.

CHAPTER VIII

DISCUSSION

A. GENERAL CONSIDERATIONS

The general goal of this large study was to provide data to support a feasibility analysis for the use of plants for wastewater purification. The experimental program was designed to test the NFT under conditions that would make it a viable alternative to conventional technologies. Units up to 36 meters long were tested at flow rates up to 11,000 liters (3,000 gpd) per day. Although a detailed costing analysis is beyond the scope of this study, it appears that the NFT will achieve the goal of being competitive with most conventional technologies; that is, secondary treatment efficiency or better can be achieved with the NFT system for a similar or lower cost.

The testing program was conducted in such a way that a given loading rate was tested to the point of achieving relatively constant results, and then an increased loading rate was imposed on the system until treatment failure or plant death occurred. This approach resulted in the testing of plant systems that were relatively immature under highly adverse conditions. Thus, the results of this study should be considered conservative. Since the results also reflect plant activity in a cold climate, the capability of the system should improve with higher incident solar radiation and temperature. The disadvantages and the advantages of the NFT system over conventional treatment systems are listed in Table 8.1. In general, this study provides the information that enables all plant species to be considered as potential candidates for a wastewater treatment system. The weeds and other marginally valued plants can all be useful, but the NFT enables consideration of trees, shrubs, food plants and pharmaceutical producing plants as potential candidates. Existing agricultural practices for propagation, growth, harvesting and pest management can be applied to the NFT system. The operation of units in northern New York and New Hampshire indicates that a cold climate is not a severe limitation and that the system would operate anywhere in the contiguous United States. Another possible advantage of the NFT system is the value of the potential by-products when ornamental, food or biochemical products are considered. As will be indicated under the cost anaylsis, the covered system and the size of the NFT that is required to provide effluent quality appears to be competitive with the conventional treatment systems. Finally, a significant advantage is the psychological impact of a treatment system which produces a beautiful and potentially valuable by-product from a wasted resource. The impression gained from a bed of roses in blossom when visitors enter the sewage plant provides a significant asset for the treatment system.

TABLE 8.1. ADVANTAGES AND DISADVANTAGES OF THE NFT SYSTEM WHEN USED FOR WASTEWATER TREATMENT

ADVANTAGES

1. All plants are potential candidates
2. Existing agricultural techniques applicable — propagation, growth, harvesting, pest control, etc.
3. Not limited by climate — applies anywhere in U.S.
4. Potentially valuable by-products
5. Covered system cost-effective compared to conventional
6. Psychological impact of treatment system appearance

DISADVANTAGES

1. Limited by all factors that apply to biological treatment
    - toxic response
    - seasonal affects

The major disadvantages that limit the application of the NFT system are essentially those that apply to all biological systems. The recovery of the system from toxins will be slow and costly. In northern climates the seasonal effects are significant and will affect effluent quality.

Due to the interaction of the large number of variables in the NFT, it was difficult to define all of the mechanisms affecting pollutants in domestic sewage. Parameters that are important will be discussed below. However, several general observations can be made, regardless of the climate and location of the NFT system. Effluent total COD concentrations of less than 100 mg/ℓ, BOD_5 values less than 30 mg/ℓ and suspended solids less than 10 mg/ℓ were often achieved at loading rates of 20 cm/day with NFT unit lengths of 24 and 36 meters. Effluents of less than 10 mg/ℓ of suspended solids occurred under loading rates of 30 cm/day with the longer test cells under virtually all conditions.

In general, the plant productivity and nutrient removal aspects of the NFT were not remarkable. This is attributed to the low temperature and incident light conditions in combination with the high loading rates of domestic sewage pollutants that were examined for most of the test period. The original system was proposed to be useful for manipulating the nitrogen cycle via nitrification-denitrification. However, conditions never enabled nitrification to occur to any significant degree.

B. NFT CHARACTERISTICS AND POLLUTANT REMOVAL MECHANISMS

B.1. Settling, Filtration, and Suspended Solids Control

The accumulation of solids in the root mass leads to the possibility of pollutant manipulation in the NFT system. Background suspended solids lost from a biological processing NFT can be estimated from the synthetic sewage studies since the influent solids were always low. At lower loading conditions of 5 to 20 cm/day of a synthetic soluble wastewater, effluent suspended solids resulting from microbial growth were always less than 5 to 7 mg/ℓ, and these usually occurred in a coagulated, flocculated form so that the effluent clarity was quite high; in other words, the turbidity was low. At the higher loading rates, effluent suspended solids never exceeded 10 mg/ℓ.

A consideration of the loading rates and the average flow-through velocities indicates that most suspended solids should be easily removed at relatively high loading rates in the NFT system. What is undefined are the mechanisms that encourage small, colloidial-sized bacterial solids to coagulate and form larger particles that could be removed from the system by sedimentation and filtration processes. It was anticipated in the hypothesized system that the solids would attach and concentrate within the root mass. These solids would then gradually induce additional root production so that the root depth would increase and thus provide a mechanism for suspended solids stabilization and control. In most cases, this did not occur. The suspended solids were effectively biocoagulated in the unit, but they remained relatively light and flocculant, and moved freely in the system. The results of this interaction suggest that the controlled hydraulic loading and unloading of these units could lead to separation and accumulation of suspended solids in the reactor. At a specified time these solids could then be flushed from the system in a relatively concentrated form. This alternative was tested in the latter phases of the study and was found to be effective for the treatment of raw sewage. Intermittent loadings of 30 cm/day were found to result in complete removal of settleable solids, 89 percent removal of suspended solids, and 77 percent removal of COD. These extraordinarily high efficiencies were achieved in short-term experiments and should not be taken as conclusive results; but they do represent an encouraging optimization of the system.

The solids control capability of the NFT system and manipulation represents one of the important advantages of the NFT system. In short-term experiments attempting to document the capability for accumulating solids and the rate of accumulation of solids it was found that biomass entrapped in the root zone often equalled 1 kg/m^2 and that it accumulated at rates of between 2 and 548 gm/m^2/day (See Tables 7.4 and 7.5). This large amount of microbial solids represents an interesting reservoir for manipulation of various pollutant removal mechanisms. This large organic reservoir combined with low redox potential, is one of the reasons for the efficient cadmium removals, for example.

The accumulation of solids in the NFT system is predictable based on the biodegradable organics and the suspended solids in the system. For example, if it is assumed that 80% of the suspended solids and BOD are removed from a domestic sewage, then 200 mg/ℓ of suspended solids and approximately 160 mg/ℓ of BOD would be removed based on a medium strength domestic sewage. The minimum microbial yield under these conditions is approximately 32 mg/ℓ of refractory microbial suspended solids and about 50 mg/ℓ of remaining undegraded suspended solids. Thus the wastewater can be considered to add approximately 80 mg/ℓ of solids that could be entrapped within the root zone if removed from the wastewater. At a loading rate of

10 cm/day, it would be expected that each square meter would accumulate approximately 8 gm of suspended solids per day, and this would increase proportionally with the hydraulic loading rate. Since these organics are relatively concentrated, this adds approximately 0.013 cm/day of organic matter. Based on the concentration that accumulates in the system and the total mass in the system, it can be assumed that the solids retention time in the NFT root zone is high, being greater than 125 days in a mature NFT system. This long solids retention time of coagulated solids in the root zone represents a large population of microorganisms that could be used to manipulate many of the pollutant cycles. The capability of this microbial community was limited in this study because of the high loadings that were tested under most conditions and the resulting low dissolved oxygen levels.

The efficient biocoagulation and separation of organics from settled and raw sewage indicate an important role for plants in achieving solids separation. This may be an alternative to clarification processes. Clearly, the accumulation and the use of this large amount of organic matter must be limited to application of plants that can withstand low dissolved oxygen levels and redox potentials. Swamp plants such as bulrushes and cattails are excellent candidates for this particular part of the system.

B.2. Microbial Metabolism and BOD and COD Removal

Microbial metabolism of the BOD must be the main organic removal mechanism. This in turn is controlled by the oxygen aeration rates. Organic removals were less impressive than suspended solids removals. Typical effluents of less than 10 mg/ℓ BOD occurred when treating sewage in the 36 meter long units at loading rates of 7 cm/day. At the higher loading rate of 20 cm/day the effluent BOD increased to 40 mg/ℓ. At this higher loading rate the dissolved oxygen levels were often close to zero throughout most of the length of the system. Even at the lower loading rates dissolved oxygen was usually no greater than 2 or 3 mg/ℓ, indicating significant microbial activity.

The high efficiency of syspended solids control and lower capability for BOD control indicates several possible alternatives for configurations of the NFT system. For example, high rate preliminary treatment NFT units could be used to efficiently separate solids and achieve perhaps as much as 50 percent BOD removal. Aeration by a low energy-consuming technique such as cascades could be inserted between this roughing NFT system and the following organic removal step. High rate processes that efficiently remove organics might be considered for installation after this unit prior to the addition of a polishing and nutrient removal NFT section.

Although it was difficult to quantify the relationship of the plant growth to the loading condition, the dissolved oxygen and the organic loading rates were clearly a major controlling factor for plants that do not have physiological adaptations for growing in anaerobic environments. For example, long-term tests indicated that influent organic loadings with 12 meter long units at 20 cm per day exceeded the tolerance of the reed canary grass. Long term operation at 20 cm/d at BOD values of 200 mg/ℓ or greater would kill healthy reed canary grass in several weeks. Also, several days' submergence of a root mat, such as that of napier grass, would result in death of the plant.

The low turbidities that we achieved at relatively high loading rates were a direct result of the biocoagulation that occurred in the system. An example of the clarity of the effluents can be seen in Figure 8.1 showing the accumulated solids in the bottom of an overflow trough and high clarity water being discharged from the unit. Efficient separation of solids throughout the testing indicates that alternate flushing and sedimentation may be necessary and useful to obtain complete control over solids in the system. High turbidity effluents should be expected during flushing cycles.

Finally, it should be emphasized that roughing NFT systems operating at low or zero dissolved oxygen concentrations should be expected to generate malodors. Since in the northern climates a greenhouse is required, it should be possible to separate these odors and to strip them before discharging the air from the greenhouse. Odors in subsequent portions of the system were insignificant throughout most of the study.

Efforts were made to estimate the impact of the NFT on reaeration characteristics, and indirectly to determine the role of the plants in organic oxidation. Due to the complexity of the factors affecting reaeration, no conclusive insights were developed. Attention to this topic in future studies will assist in optimizing alternative NFT configurations for organic removals and nitrogen cycle manipulations.

B.3. Nutrient Removals

The use of plants for nutrient control is an old technology, especially with the application of microscopic algae in wastewater ponds. This use of plants for nutrient removal, however, raises several problems. Large land areas are usually required. Figure 8.2 illustrates the relationship between nitrogen content and yield of plants and the area required to treat domestic sewage based on nitrogen removal. Exceptionally high plant yields are required for nitrogen control before the land area requirements are small enough to represent practical treatment areas, especially where greenhouse covers may be necessary. Literature values indicate that many of the plants that were studied, such as cattails, have the capacity to yield up to 80 t/ha-yr when the root mass is included. With the higher nitrogen content, this plant yield is such that as few as 15 ha of land would be required for nitrogen removal from sewage produced by 10,000 people. However, this represents a large surface area, and one that would be costly to enclose.

It is likely that lower efficiencies for nutrient removal would be achieved with the NFT system. Another possible limitation for nitrogen and phosphorus removal with plant systems is the relationship between the nitrogen and phosphorus in sewage and the ratio in plant matter. The concentration ratios of nitrogen to phosphorus can be as low as 2:1 in settled or secondary treated sewage, whereas plants often have a nitrogen:phosphorus ratio of 10:1. Certain plants also have other requirements that raise special problems when applied to domestic sewage. For example, many plants require large quantities of potassium and iron, two elements found at low concentrations in domestic sewage.

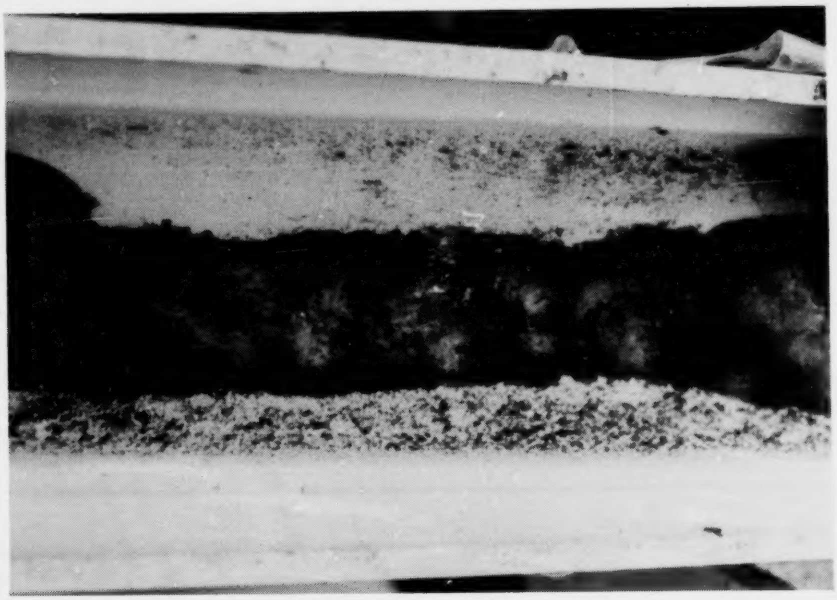

Figure 8.1. Photograph of the effluent from an NFT unit treating primary settled sewage showing the the large coagulated particles settled in the overflow trough.

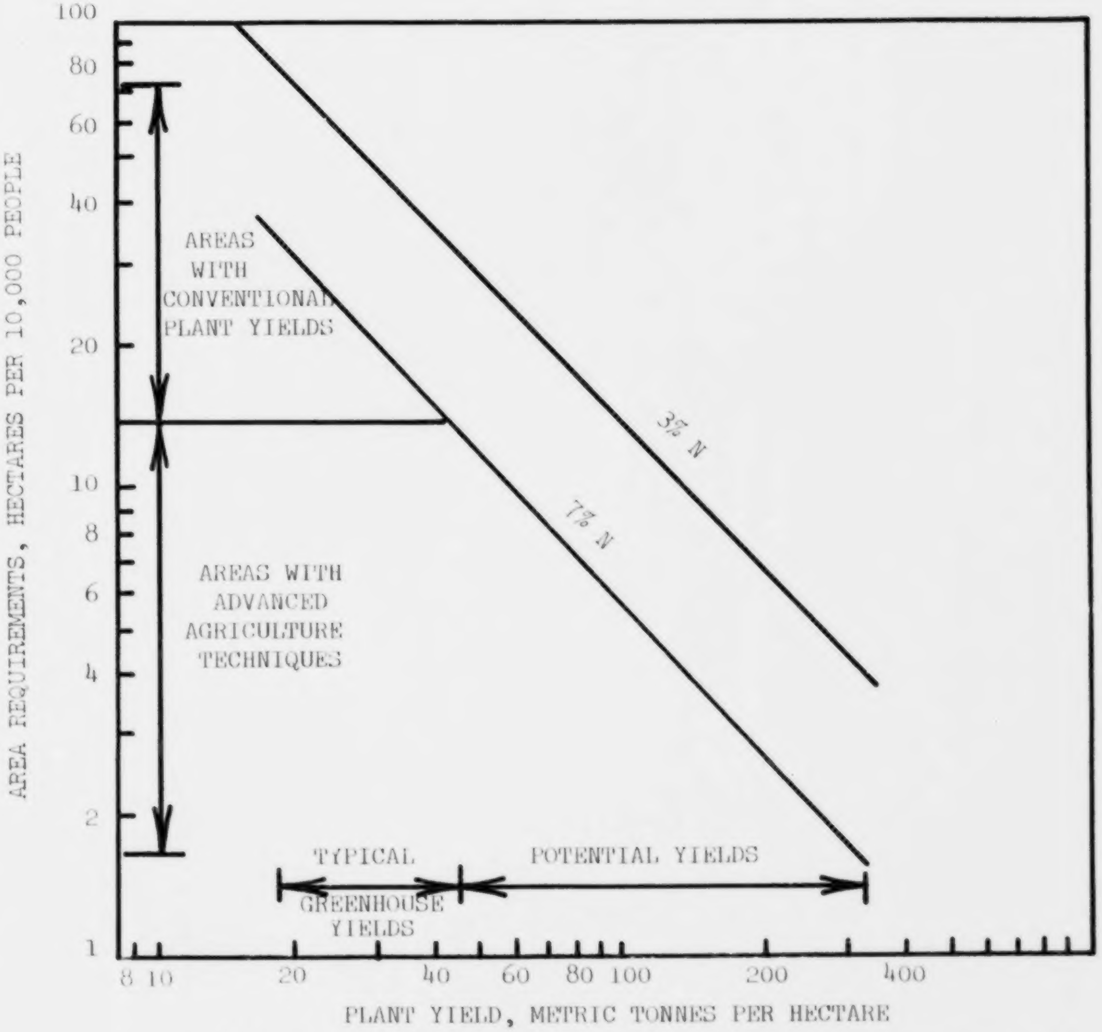

Figure 8.2. Relationship of plant yield to land area required for complete nitrogen removal from domestic sewage for crops with two different levels of nitrogen. It is assumed that the sewage has 40 mg/ℓ of total nitrogen, that it is all available to the plants at the initial high rate of uptake, and that the per capita flow rate is 0.4 m^3/d (100 gpd).

In tropical areas nutrient removal with the NFT may be more promising. However, in the colder climates the attractiveness of nutrient control is limited. It is likely that the nutrient film can be used to produce valuable plants and a marginal nutrient removal efficiency. Where additional nutrient removal is required, a combination of other higher rate biological and chemical processes may be required. Finally, it should be noted that in areas where seasonal discharge limitations are acceptable, biological processes such as the NFT may be useful. Significant nutrient removals can be achieved in the summer periods where temperatures are higher and light intensity greater in temperate climates, but during the colder times of the year when low radiation occurs, little nutrient removal may result.

C. TOXIC SUBSTANCES

Data obtained on heavy metals and toxic organics indicate that the NFT can effectively remove toxic materials. Zinc and cadmium concentrations of 0.1 to 0.3 mg/ℓ were efficiently removed from the wastewater down to a level of 0.06 mg/ℓ or less, thus meeting effluent standards for irrigation and higher quality uses. These metals were concentrated in the volatile solids entrapped by the roots. The efficiency is probably related to microbial activity and the low redox potential. However, a significant portion of the cadmium that was removed from the wastewater was transferred into the foliage of the reed canary grass. Any use of the plant material must take into consideration the concentrations of the toxic metals in the plant matter.

The NFT unit also appeared to be efficient in removing volatile and non-volatile organics. As in overland flow land treatment, the large surface area of the NFT enhances the chances of losing volatile organics such as chloroform (Jenkins, 1981). Non-volatile toxic organics such as PCB's appear to be absorbed in the root zone. This stripping of toxic organics needs to be defined in future activities so that the fate of these materials can be predicted.

Although it was not anticipated that the indicator bacterial organisms' reduction would be significant enough to result in the elimination of a disinfection process, significant removals could occur if the NFT system were optimized. The lower loading rate condition usually resulted in large decreases in fecal coliforms.

D. TDS MANIPULATION

The introduction of the NFT system provides the design engineer with the use of the entire plant kingdom as treatment mechanisms. There is potential for dissolved solids control with plants under certain circumstances when using the NFT system. This possibility, however, may not be realized since the uptake of dissolved salts is closely related to plant yield and evapotranspiration. The relationship between plant yield and dissolved solids control is illustrated in Figure 8.3 where three different loadings are compared to varying plant yields with varying ash content. With most

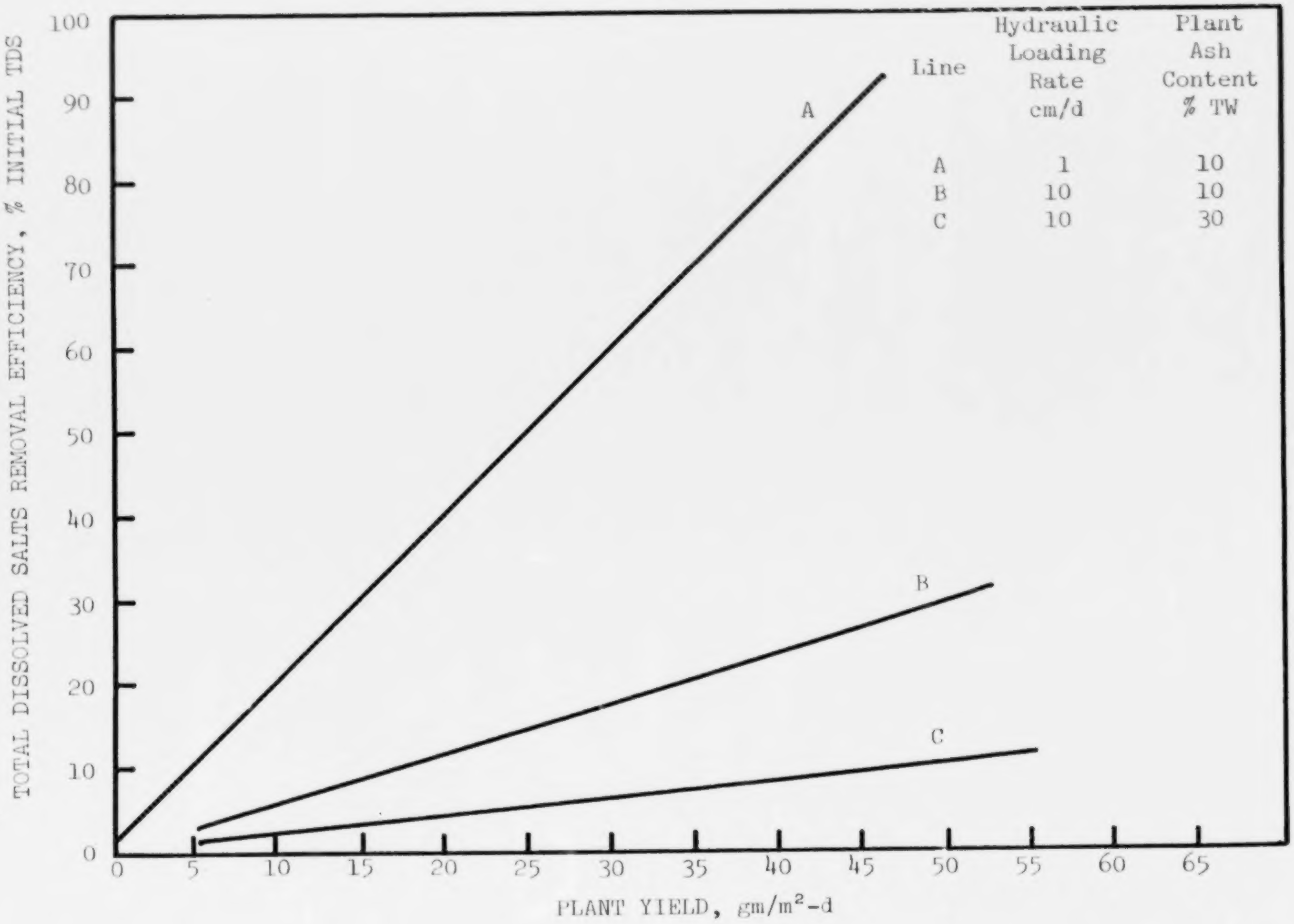

Figure 8.3. Calculated maximum total dissolved salts removal efficiency with plants in the NFT at varying yields. The influent total dissolved solids concentration is assumed to be 500 mg/ℓ. ET is assumed to be zero.

plants that have relatively low ash content, efficient removal of dissolved solids could occur, but only at extremely high yields. Note that it is assumed that ET is zero in Figure 8.3, a simplifying assumption that does not occur in plant metabolism.

E. TEMPERATURE EFFECTS

The effect of temperature on the NFT treatment system has both negative and positive aspects. Studies with the NFT indicate that plants that maintain their roots in warmer solutions can withstand relatively cold temperatures around the vegetative portions and still grow at significant rates. Root temperatures of 10°C will be expected in all but the most northern climates. Temperatures as low as 7°C occurred in New Hampshire. This did not kill the plants, but it did limit their productivity. It is anticipated that the heat provided from the sewage would minimize the amount of heating for the greenhouse that would be required in northern climates in order to maintain acceptable air temperatures. The combined use of solar greenhouse techniques with large water flows with minimum temperatures of 10°C could eliminate the need for additional heating with marginal quality plants.

The negative aspects of the temperature effects relates to the solar heat absorption that occurs in the greenhouse and the possibilities of thermal pollution effects. The large surface area required to treat the sewage provides an ideal opportunity to capture solar heat in the water. When feeding colder temperature sewage at 7°C, temperature rises greater than 10° were observed in January and February in New Hampshire. In the summertime the temperature increase appeared to be less, although this may have reflected the impact of shading by the more mature plants that were tested in most summer operations. The relationships of temperature and greenhouse requirements should be contrasted to the storage requirements with land application systems. In the northern U.S. climates, more than 10 ha of wastewater winter storage would be required for a population of 10,000 people.

Another advantage of a greenhouse cover is that it enables complete control of pests and pest management techniques. Biological controls (such as with the ladybeetles tried here) and chemical controls are easily contained.

F. PROCESS SENSITIVITY AND DESIGN

The relationship between the major loading rate parameters and the efficiency for various pollutant removals were examined to provide a predictive relationship between wastewater quality, NFT area, and effluent quality. Several loading rate parameters affect the removal mechanisms. The hydraulic and weir loading rates to the system dictate the efficiency of the suspended solids and BOD removals, and also indirectly determine the hydraulic retention time, which influences other pollutant removal mechanisms. The Results section outlined techniques to relate the loading rate to the hydraulic retention time under a specific set of conditions. Unfortunately, due to the large number of variables (plant species, reactor length, depth of liquid, temperature, incident radiation, and pollutant concentration) no consistent theory of kinetics of removal for each pollutant was defined. However, empirical removal rates at given loadings can be used as a first approximation of the size of the system required to achieve a given effluent. The dissolved synthetic sewage used at Cornell generated by the Cayuga Heights community in New York, and that of the Hanover, New Hampshire, community were similar within certain limits, and can be used for empirical estimates of process sizing and efficiencies.

As indicated in the Results Chapter, loading rates up to 20 cm/day resulted in effluent qualities exceeding secondary standards in most cases. The removal rates reported in Tables 7.22 and 7.23 express the range of removals achieved at the varying loading conditions. During lower loading rates the systems worked more efficiently, while at higher loadings the systems were receiving more pollutants and were operating less efficiently for many of the pollutants. Given a loading rate, the area required for treatment can be calculated from the removal rate when it is expressed as kilograms removed/ha-day. For example, if the COD removal rate of 900 kg/ha-day could be achieved continuously in an NFT system, a design loading rate of 4500 m^3 applied/ha-day would result, or a hydraulic depth of loading of approximately 45 cm/day would be acceptable (assuming that the COD concentration is 0.2 kg/m^3). The hydraulic retention time that is required to produce this effluent is not known specifically; however, the volume of the system with a given application rate defines the hydraulic retention time. In this case the hydraulic retention time in a 36 meter long unit would be approximately 95 minutes if the system responded similar to the test given in Figure 7.45. Deeper or finer root masses with varying void spaces and accumulation of different levels of biomass will change the system's volume and thus the hydraulic retention time. The relationship of hydraulic retention time to efficiency is an area where much additional work needs to be conducted before rational design of the NFT process is possible. Example loading rates and removal rates are listed in Table 7.23 for removal of nitrogen, phosphorus, and cadmium as obtained from the empirical loading rates that were achieved in the system. Bench scale kinetic work also provided the removal rate values which can be contrasted to those obtained under steady state with the larger system. Maximum BOD removal of 50 gm/m^2-day were measured with small reed canary grass units. This indicates that an application of 25 cm/day would result in an acceptable secondary effluent.

G. PLANT ENVIRONMENT FACTORS

A wide range of plants were tested to determine their viability under varying loading conditions and adverse environmental conditions. Although a large amount of information remains to be developed to define the specific conditions that will lead to maximum yields, considerations for plant production, harvesting, and management were defined in this study. The main candidate species, reed canary grass, was used throughout the study and was found to be viable throughout the four seasons in the cold climate of the United States. However, the most sensitive parameter appears to be related to the organic loading rates on the root system and, indirectly, to the dissolved oxygen concentration. At a 20 cm/day loading of medium strength sewage, the reed canary grass will eventually die. The reason for this death is likely the lack of dissolved oxygen reaching the root system to provide metabolic requirements. In actual systems it is recommended that the organic loading rate be limited when plants that require an aerobic or facultative root system are utilized. This can be accomplished in a sewage treatment system by utilizing a roughing treatment unit upstream from plants that are more sensitive. Plants that feed oxygen to the roots through their structure, such as the bulrushes, may be viable for encouraging the biocoagulation and stabilization of sludges. The extent of aeration caused by such plants was not measured in this study.

It is essential that the photoperiod and temperature interactions be carefully evaluated in choosing a plant species. One candidate species tested, phragmites, grew rapidly during the warmer parts of the year; but when the photoperiod declined to a certain duration, phragmites became dormant; and growth ceased until the photoperiod reached the minimum length. In New York the dormant period occurs between mid-December through the first of March. Phragmites' dormancy and reaction to the light period was in contrast to the reed canary grass, which remained green and healthy throughout several years of testing in the NFT unit. Surprisingly, the tropical napier grass also remained green and growing throughout the entire year.

It should be emphasized that the combination of organic loadings and low oxygen tension in the root zone provide an inhibitory environment for many plants, and the presence of large quantities of bacteria and organic matter provides an excellent environment for the growth of pests. As indicated in the Results section, numerous crises were experienced where a pest would grow to a point that would threaten the entire plant system. In all cases, the organism was controlled by a plant management scheme, by manipulation of the water flow, or by the addition of pest controls. It is essential in considering this type of system that the expertise gained in greenhouse and plant management be used since all of the problems that occurred have essentially been solved by plant scientists. A full scale NFT system would require the services of a horticulturalist or other plant specialist.

In general, the more valuable plants would be exposed to the wastewater at a point in the system where the stress on the plant would be minimzed. In other words, the roses that were produced in this system grew well when the sewage had received treatment to a level that removed most of the biodegradable organics and suspended solids. This suggests that the latter part of the NFT system where the wastewater is relatively clean could be used for production and testing of a number of different species for community or commercial utilization.

H. OPTIMIZED FACILITY CONSIDERATIONS

The pollutants which must be removed from sewage range from the large solids to toxic trace organics. The fundamental mechanisms that control their removal may not be compatible with one another. For example, a continuously flowing system where the biochemical materials are exposed to the bacteria is the most favorable environment for rapid removal. However, suspended solids management may be achieved under quiescent conditions much more readily than in a continuously operated film unit. It is also likely that the solids accumulation within the reactor will be useful for further pollutant reduction if they can be accumulated in the root zone and intimately mixed with the wastewater over a short period of time and efficiently removed.

Consideration of the pollutant removal mechanisms and the NFT requirements in terms of oxygen in the root zone and photoperiod led to an optimized alternative that was tested in the latter phase of this study at the Cayuga Heights plant. For maximum accumulation of solids in the anaerobic root zone of roughing plants such as cattails and bulrushes, a rapid addition of wastewater to the system followed by quiescent draw off into subsequent units used to polish the remaining BOD and suspended solids was tested. The preliminary results from this testing show that at an overall addition of 30 cm of raw sewage per day, 100 percent of the settleable solids was removed and contained in large particles that were biocoagulated; 75 to 80 percent of total COD was removed; 90 percent of the suspended solids was removed; and, surprisingly, 60 percent of the total nitrogen was removed from the wastewater. These results lead to the consideration of an exceptionally small system for roughing treatment followed by a polishing secondary system that would have water of a high enough quality that many alternate species could be produced without dissolved oxygen and solids inhibition in the root zone. These data suggest that the roughing treatment unit could achieve better than primary treatment with less than 0.5 ha for sewage flow from 10,000 people (1 MGD). By removing the suspended solids and the BOD rapidly in this system, further treatment and some additional nutrient removal could be achieved with several hectares of NFT following this roughing batch mode type of treatment. This will be the type of design discussed in the following chapter.

I. PLANT CULTURING AND PROPAGATION

The wide range of testing with weeds and valuable commercial plants conducted in this study indicates that nearly all plants can be considered candidates for use in the NFT system. By using culturing techniques such as propagation with cuttings, it is relatively easy to produce large plant stands. In cases where seeds are available with plants such as cattails, it is also possible to rapidly produce large stands of these plants.

The major limitations for the plant culturing aspects of the system relate to the practical consideration for installation of the system. If plant culturing takes place after construction it would be necessary to begin plant production in the spring when the sources of plants are available as young plants or as seeds. Winter start-up would be a difficult task. However, there is also the possibility that while the facility is under construction large quantities of plants could be propagated by growers, or temporary facilities could be constructed to produce large quantities of the material. For example, temporary NFT propagation units could be established during warmer weather by spreading plastic on top of the ground and allowing water to be sprayed as a fine mist over such a surface. This would be one alternative to providing plant systems that would be available at the finish of construction.

It should also be noted that the latter sections of the NFT unit can be used as culturing and propagation sections for other portions of the facility. It should be anticipated that pests have the capability of eliminating portions of the system at any time, and it would be wise to have replacement materials available so that portions could be removed and replaced with new plant matter. Another option for the latter portion would be to use it as a nursery area for production of valuable plants for either commercial sales, or for use in the municipality.

CHAPTER IX

NFT TOTAL SYSTEM FEASIBILITY CONSIDERATIONS

The following total system requirements and some economic estimates provide a perspective on the potential of this technology. Due to the promising results obtained from the large size and the duration of these tests, it is hoped that this information will lead rapidly to innovative testing of the NFT process in larger pilot operations and possibly in full scale operation. The following analysis is divided into two areas. First is a consideration of an alternate secondary wastewater treatment system, and second, the application of the NFT as the main unit process in tertiary treatment or water reclamation. Both examples are based on a system large enough to treat wastes from a community of 10,000 people (wastewater flow of about 3800 m^3/d or 1 MGD).

A. THE NFT AS A SECONDARY TREATMENT SYSTEM

A secondary NFT treatment system that would produce effluent quality with less than 30 mg/ℓ of BOD and suspended solids throughout the year, even in a northern climate, was developed using the conservative data of this study and is illustrated in Figure 9.1. This system is composed of a two-phase NFT treatment. The first phase is an intermittently loaded roughing NFT designed to remove all of the settleable solids and a significant portion of suspended solids and BOD. It has a covered greenhouse area of about one hectare per 10,000 people served. It is followed in sequence by a polishing treatment system which has a greenhouse area of approximately two hectares. The loading rate on the roughing system is approximately 50 cm/day, and the polishing area receives a flow equivalent to 25 cm/day. The overall loading rate on the entire treatment system is equivalent to 17 cm/day.

Potential plant species for the system include a variety of the submerged aquatics such as bulrushes, cattails, and sedges for the roughing treatment system. The polishing unit would be composed of rapidly growing plants with large root systems such as the napier grass and the reed canary grass. Approximately one-third to one-half of the latter unit could be used for the production of useful plant materials—ornamentals, trees, and shrubs.

It is beyond the scope of this study to perform a detailed design and costing of the system. However, some general comments regarding the economics of the NFT can be made. The unit shown in Figure 9.1 would be built with a low-cost solar greenhouse type of construction. The greenhouse has a capital investment of approximately $54/$m^2$ ($5/$ft^2$). Thus the total capital investment for the entire treatment system, minus the sludge handling, would be approximately $1.6 million for a sewage flow from 10,000 people. This

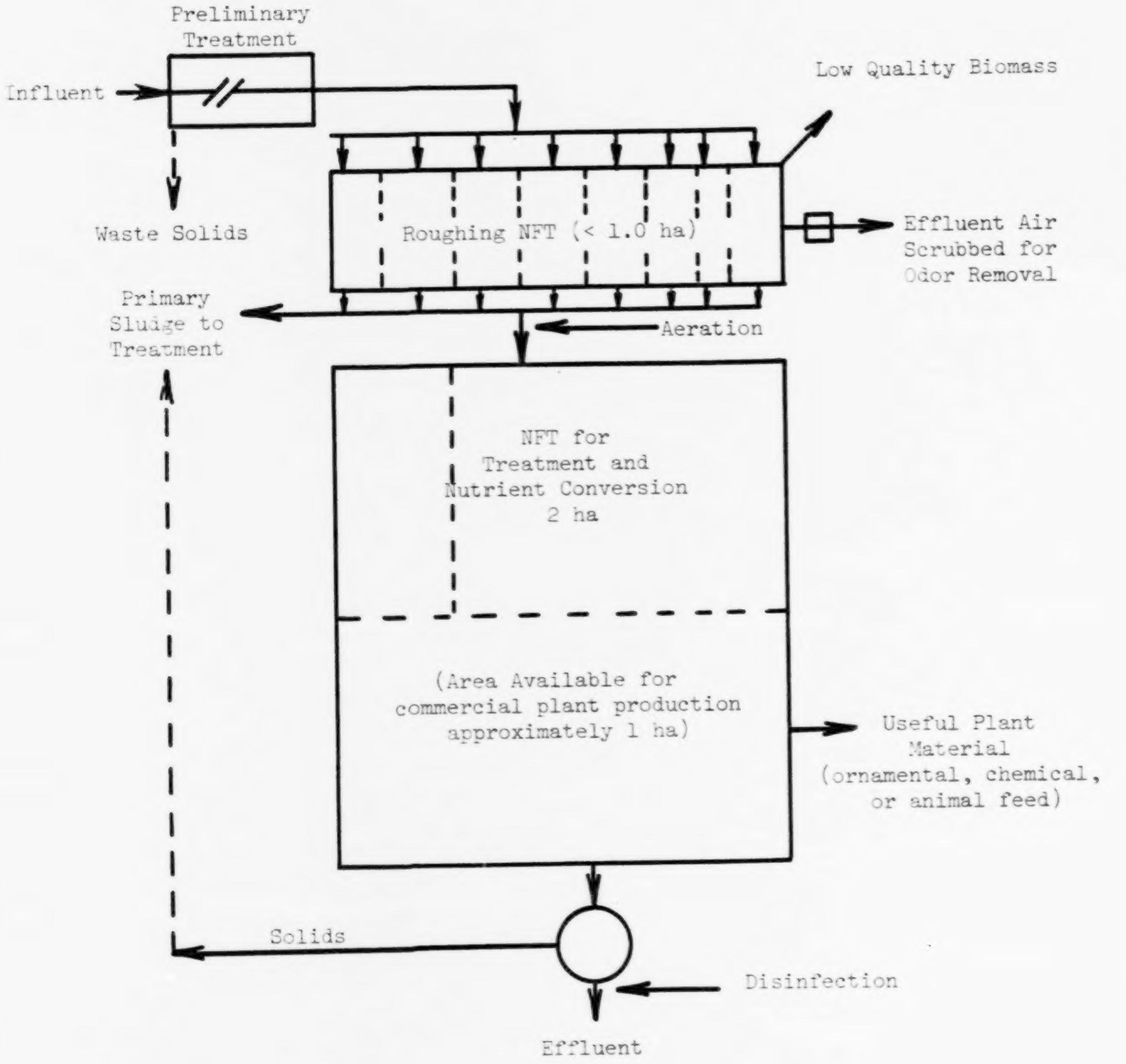
Preliminary Treatment
Influent
Waste Solids
Low Quality Biomass
Roughing NFT (< 1.0 ha)
Effluent Air Scrubbed for Odor Removal
Primary Sludge to Treatment
Aeration
NFT for Treatment and Nutrient Conversion 2 ha
(Area Available for commercial plant production approximately 1 ha)
Useful Plant Material (ornamental, chemical, or animal feed)
Solids
Disinfection
Effluent

Figure 9.1. Schematic of NFT treatment facility capable of treating domestic sewage from 10,000 people.

contrasts to an average capital investment for conventional technology on the order of $2 million for a total treatment facility for the same flow. Energy requirements for this facility also appear to be low, since no aeration and only low head pumping would be required.

Although it is difficult to compare systems, it is interesting to contrast the area requirements, energy, and economic benefits of a conventional treatment system, a water hyacinth aquatic treatment system, and an NFT. An attempt to summarize these comparisons for a flow from a 10,000-person community is shown in Table 9.1. When applied as a secondary treatment process, the energy produced from the biomass grown in an NFT process is insignificant unless anaerobic digestion is used for treatment of the sludge. In contrast, the water hyacinth has an energy production value equal to approximately $0.08 per 3785 liters (1,000 gallons). However, this is a misleading value since the cost of handling the added wet material in the form of the water hyacinth is often neglected. As shown in the table, the estimated sludge produced by a water hyacinth facility is more than four times that produced in either the conventional faciltiy or the NFT facility. If this is considered, the sludge disposal costs in the water hyacinth system may eliminate all economic benefits from the energy produced in that system. In contrast, the potential value from the use of a small portion of the latter part of the NFT system can be equal to $0.40 to $0.80 per 3785 liters (1,000 gallons) treated. This by-product value assumes that useful and economically viable plants are produced from only one-sixth of the area of the NFT unit. If more area could be used to produce commercially viable plant matter, the NFT would clearly be more attractive.

TABLE 9.1. SUMMARY COMPARISON OF TWO SECONDARY TREATMENT TECHNOLOGIES COMPARED TO AN NFT SYSTEM (all achieve effluents of 30 mg/ℓ of BOD and SS).

	Conventional Biological Treatment	Water Hyacinth	NFT
Area Needs, ha	2	6	1
Energy Production, Cents/3785 ℓ (1000 gal)	0 to 4	0 to 8	0
By-Product Value Cents/3785 ℓ (1000 gal)	0	0	40
Sludge for Disposal			
Metric tonnes (wet) per year for 3800 m^3/d flow (1 MGD)	4600	19,100	5,200
% plant material	0	87	4
Sludge Disposal Costs Cents/3785 ℓ (1000 gal)	7	25	10

Note: Tertiary NFT would involve an additional 5 ha, capital cost =$3,000,000/3875ℓ/d (1 MGD), annual value of products = $1,000,000.

B. THE NFT AS A TERTIARY TREATMENT FACILITY

The use of the NFT for complete treatment of and/or nutrient recovery from sewage is a possibility which was not tested in this study. It is likely that the incorporation of several supporting unit processes and concepts would be useful in an innovative application of the NFT for tertiary treatment. The nutrient removal section of the NFT would require a minimum area of approximately 10 hectares per 10,000 population. In areas of the country where freezing weather is not a problem, this section would not require greenhouse protection. In areas south of Pennsylvania it is possible that the heat in the wastewater would minimize heating requirements.

Except under the higher light conditions, the nutrient removal from this system would not meet stringent effluent requirements. Therefore, the nutrient removal alternatives would have to consider the installation of either nutrient recovery or nutrient destruction alternatives such as nitrification/denitrification and/or other chemical alternatives. The estimated quality with and without the NFT nutrient polishing section and with the additional unit process and removal of nutrients is shown in Table 9.2. Additional research would be required to confirm these values.

The use of the NFT as a nutrient removal and polishing system raises numerous questions that can be only partially answered by this study. There may be significant opportunities for cost recovery through commercial sales of biomass products from this section. The growth of plants in a low nutrient environment may limit the number of species that can be produced in this section. However, there are plant production techniques that can eliminate substrate composition imbalances for plants. For example, for many plants foliar feeding (the application of nutrients directly to the leaf) can be utilized. This would enable high value crops to be produced in a nutrient stripping NFT, but at an additional cost for adding nutrients.

The economics of using the NFT as a nutrient recovery system remain to be defined. Although there are large greenhouses in commercial operation, the sizes proposed here are far larger than any current commercial operation. The economics, however, are attractive since the capital investment may be limited to around \$54/m^2 (\$5/ft^2) and the return per year may be one-third of this, depending on the value of the crop. The total capital investment for the nutrient stripping NFT would exceed \$6 million for a flow from 10,000 people. If, however, a significant portion of this facility could be used to produce commercially viable products, it may be an economically attractive alternative.

TABLE 9.2. ESTIMATED WATER QUALITY TO BE PRODUCED BY THE PROPOSED WATER RECLAMATION FACILITY. (Values in mg/ℓ except as noted).

	Characteristic Raw Sewage (degritted)	At Nutrient Removal NFT	After Nutrient Removal/ Polishing NFT	After Nutrient Removal/Polishing Additional Unit Process
Solids				
Suspended	200	10	<1	<1
Dissolved*	500	150	100	100
Settleable, mℓ/liter	10	0.5	0	0
Organics				
BOD	200	20	<1	<1
COD	500	50	<50	<50
Nutrients				
Nitrogen, Total	40	20	<10	<0.1
Phosphorus, Total	10	7	5	<0.1
Heavy Metals	0.1	0.01	<0.01	<0.005
Toxic Organics, ppb				
Volatiles (such as chloriform)	200	20	<5	<5
Non-volatiles (such as PCB)	10	3	<2	<2

*Plus background salts in tap water.

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APPENDIX A

General Electric Phase 0 Data

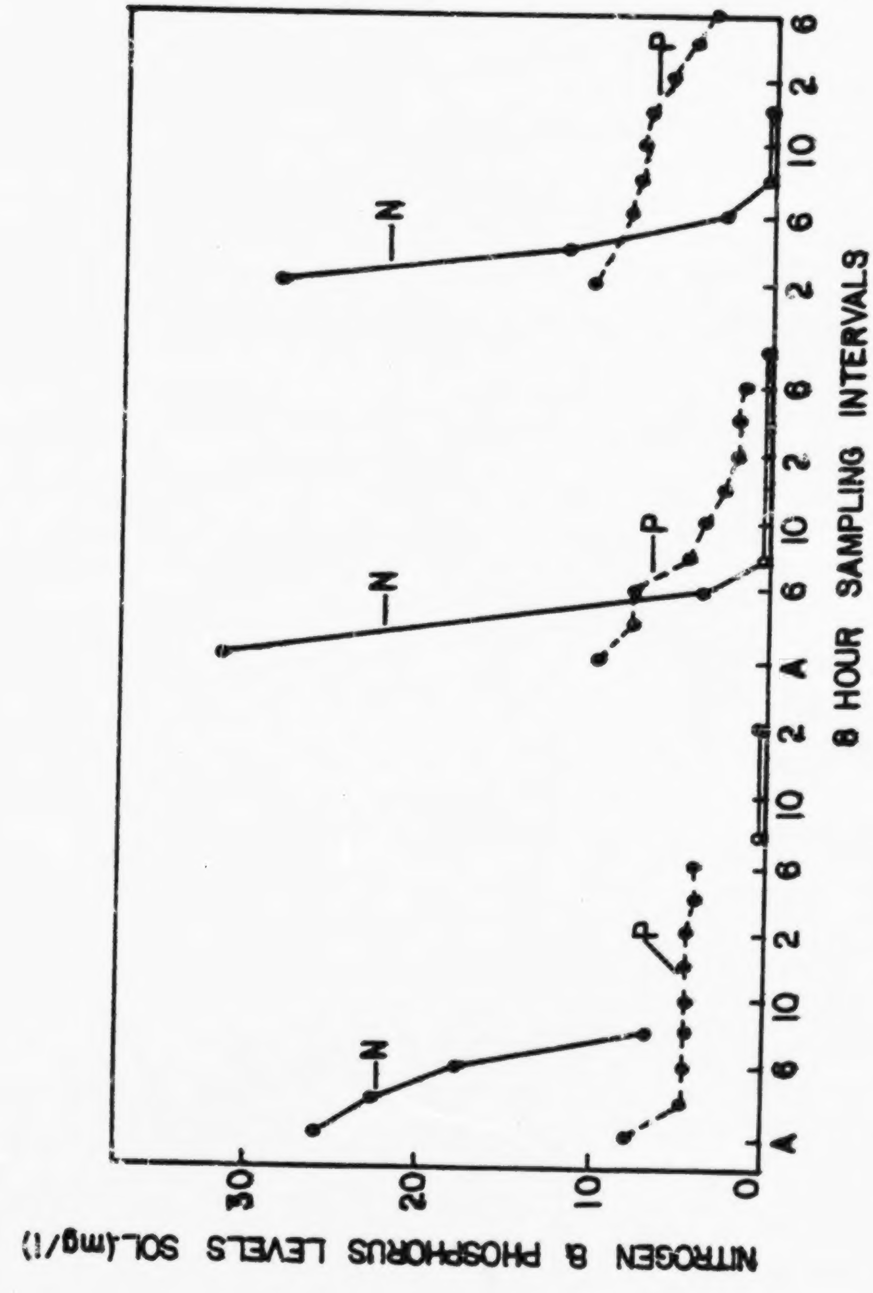


Figure A-1, Nitrogen and phosphorus removals from General Electric NFT unit containing Watercress.

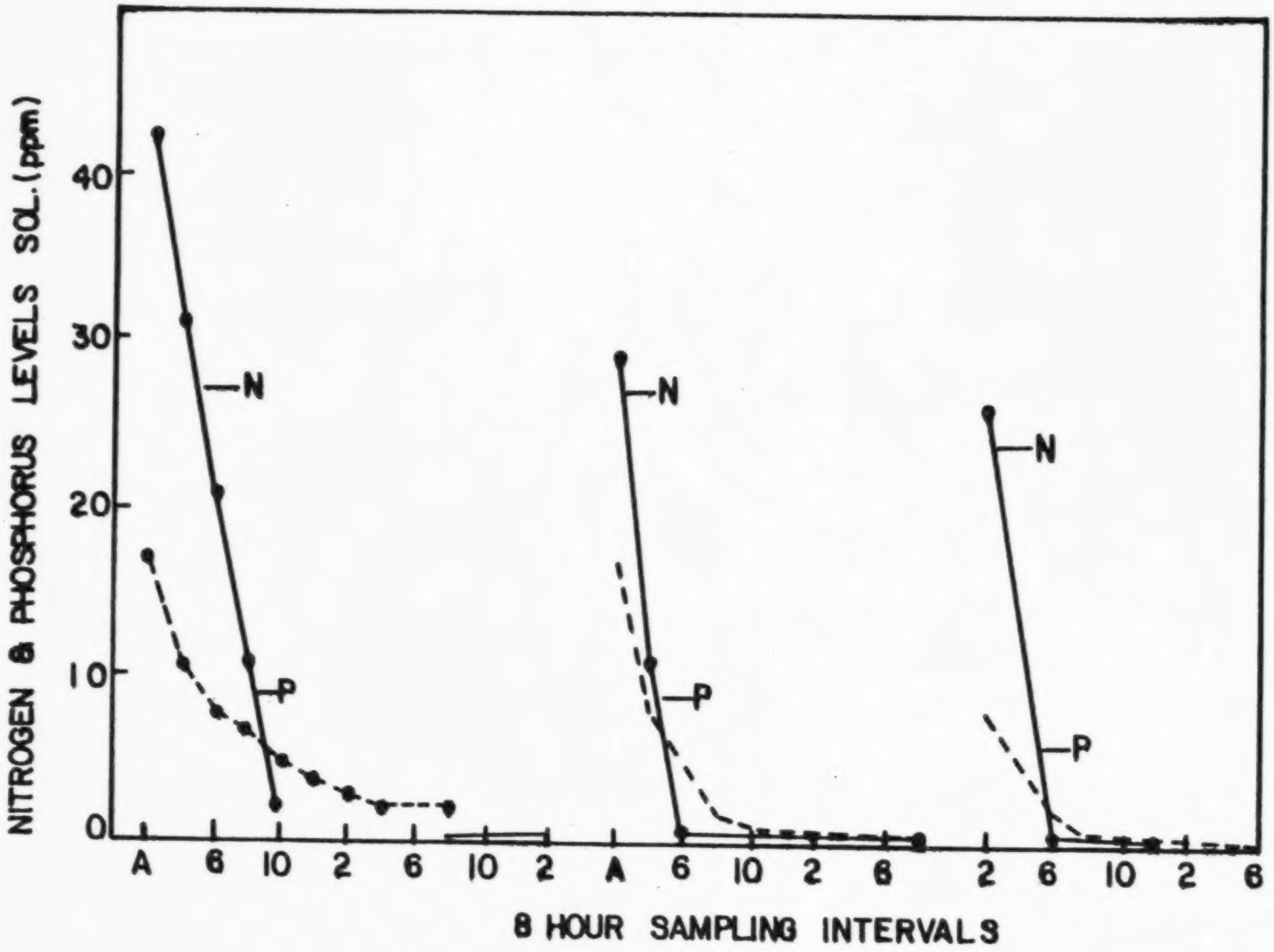


Figure A-2, Nitrogen and phosphorus removals from General Electric NFT unit containing Napier Grass.

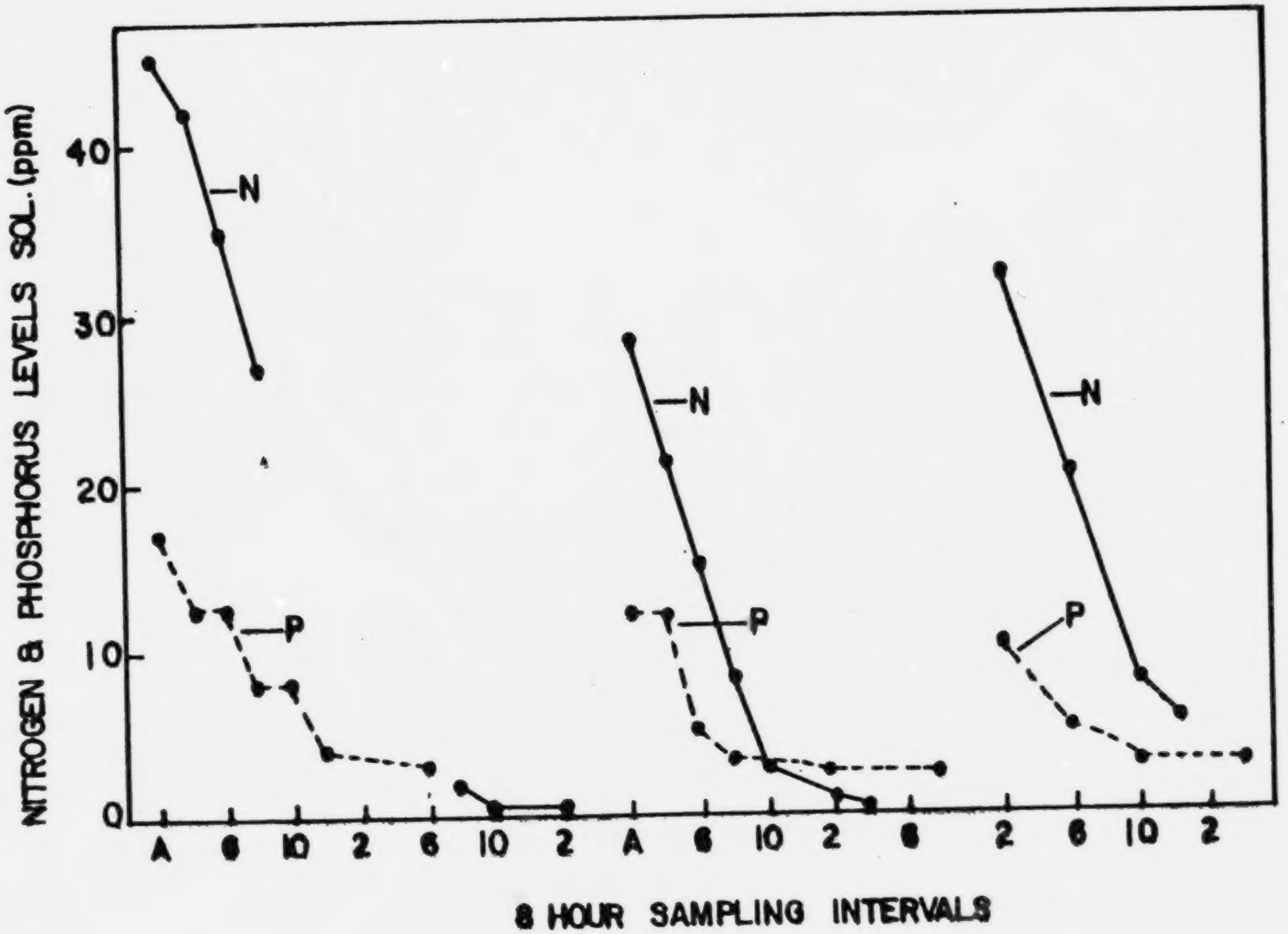


Figure A-3. Nitrogen and phosphorus removals from General Electric NFT unit containing Coastal Bermuda Grass.

APPENDIX B

This appendix presents data developed in Hanover, New Hampshire, using domestic sewage. It includes data from both the CRREL and Hanover greenhouses. Tables B.1 through B.18 present mean values for variables tested during each loading condition. The complete data set is presented in three chronological sets. The first set (Figures B.1 to B.27) shows data from the early experiments in a 7.4 m^2 system in the CRREL greenhouse. The second set (Figures B.28 to B.58) shows data from later experiments in that same system. The last set (Figures B.59 to B.113) shows data from the 27.9 m^2 system at the Hanover treatment plant.

TABLE B.1. LOADING CONDITION PARAMETERS TESTED IN PILOT SCALE NFT SYSTEMS IN NEW HAMPSHIRE USING DOMESTIC WASTEWATER. CONDITION NUMBERS ARE GUIDES TO SPECIFIC VARIABLE DATA, WHICH FOLLOWS.

	Target Loading Rate		Condition Dates				
Condition No.	Area Loading Rate cm/d	Weir Loading Rate m^3/m-d	Start	End	System Area m^2	Plant Species	Application Mode
1	5.1	0.62	11/16/79	12/2/79	7.4	Canary Grass	Intermittent
2	4.0	0.48	12/19/79	12/27/79	7.4	Canary Grass	10 min on 50 min pause
3	10.2	1.25	12/31/79	1/11/80	7.4	Canary Grass	10 min on 50 min pause
4	10.2	1.25	1/14/80	1/18/80	7.4	Canary Grass	8 hr on 16 hr pause
5	10.2	1.25	1/19/80	1/30/80	7.4	Canary Grass	20 min on 40 min pause 12 hr/d
6	5.1	0.62	1/31/80	2/8/80	7.4	Canary Grass	10 min on 50 min pause 12 hr/d
7	20.3	2.48	2/9/80	2/13/80	7.4	Canary Grass	20 min on 40 min pause 18 hr/d
8	5.1	0.62	2/15/80	4/11/80	7.4	Canary Grass	5 min on 50 min pause
9	10.2	1.24	4/12/80	6/13/80	7.4	Canary Grass	10 min on 50 min pause
10	20.3	2.48	6/14/80	6/30/80	7.4	Canary Grass	20 min on 40 min pause
11	6.9	2.49	2/13/81	3/20/81	27.9	Phragmites* Cucumber† Canary Grass§	Continuous
12	10.2	3.74	4/13/81	5/8/81	27.9	Cattail/Bulrush* Phragmites† Canary Grass§	15 min on 15 min pause
13	20.3	7.47	5/9/81	5/22/81	27.9	Cattail/Bulrush* Phragmites† Canary Grass§	30 min on 30 min on

*Unit 1, †Unit 2, §Unit 3.

TABLE B.2. SEWAGE FLOW APPLIED AND EFFLUENT FLOW FROM NFT PILOT SCALE SYSTEMS AT THE CRREL AND HANOVER GREENHOUSES. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	11	352 (77)	--	--	--
2	1	2650	--	--	--
3	6	959 (501)	--	--	--
4	2	694 (96)	--	--	--
5	4	649 (216)	--	--	--
6	3	310 (107)	--	--	--
7	2	1090 (390)	--	--	--
8	55	353 (108)	340 (89)	--	--
9	39	746.2 (200)	701 (160)	--	--
10	10	2069 (647)	1926 (644)	--	--
11	17	1565 (878)	--	--	--
12	17	3729 (1905)	--	--	3458 (1802)
13	12	5816 (951)	--	--	5563 (952)

TABLE B.3. BIOCHEMICAL OXYGEN DEMAND CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	172	4	133.2 (27.1)	33.6 (19.5)	-- --	-- --
4	109	2	116.0 (4.2)	95.0 (3.4)	--	--
5	103	2	117.0 (17.0)	38.7 (21.6)	--	--
6	62	3	148.0 (48.9)	42.3 (5.1)	--	--
7	--	--	--	--	--	--
8	58	23	121.3 (61.0)	21.8 (12.3)	--	--
9	101	12	99.9 (50.6)	21.4 (10.2)	--	--
10	133	3	51.0 (16.9)	9.6 (7.6)	--	--
11	67	4	119.4 (23.6)	71.0 (6.0)	39.5 (19.8)	10.7 (5.5)
12	182	4	136.1 (28.8)	105.2 (21.1)	74.9 (17.1)	38.8 (9.2)
13	272	3	130.7 (9.2)	88.3 (15.5)	70.8 (6.2)	53.4 (9.4)

TABLE B.4. SOLUBLE BIOCHEMICAL OXYGEN DEMAND CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	--	--	--	--	--	--
4	--	--	--	--	--	--
5	--	--	--	--	--	--
6	--	--	--	--	--	--
7	--	--	--	--	--	--
8	--	--	--	--	--	--
9	--	--	--	--	--	--
10	--	--	--	--	--	--
11	44	2	78.6 (1.9)	45.7 (6.1)	32.4 (13.6)	10.0 (2.2)
12	120	4	89.5 (9.9)	79.6 (12.9)	52.0 (14.2)	33.4 (7.9)
13	156	3	74.7 (9.5)	74.7 (5.5)	53.7 (8.8)	40.8 (8.5)

TABLE B.5. TOTAL ORGANIC CARBON CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	132	2	102.0 (8.5)	27.5 (7.7)	--	--
4	75	2	80.5 (41.7)	--	--	--
5	84	2	95.5 (13.4)	42.0 (2.8)	--	--
			(10.6)	(4.9)		
7	--	--	--	--	--	--
8	48	13	101.1 (36.9)	29.3 (9.0)	--	--
9	84	6	83.2 (36.9)	43.2 (16.9)	--	--
10	--	--	--	--	--	--
11	49	3	86.5 (21.8)	51.4 (4.4)	--	--
		4			46.0 (8.7)	24.0 (2.7)
12	101	5	75.7 (13.6)	63.2 (10.0)		
		6			50.7 (8.5)	34.3 (7.1)
13	100	2	48.0 (21.1)	45.6 (11.1)	35.6 (14.2)	24.7 (9.5)

TABLE B.6. CHEMICAL OXYGEN DEMAND CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	--	--	--	--	--	--
4	--	--	--	--	--	--
5	--	--	--	--	--	--
6	--	--	--	--	--	--
7	--	--	--	--	--	--
8	--	--	--	--	--	--
9	--	--	--	--	--	--
10	--	--	--	--	--	--
11	133	3	236.3 (4.5)	163.3 (8.0)	132.0 (21.3)	59.0 (19.5)
12	372	5	278.2 (40.9)	235.4 (35.7)	192.6 (32.6)	146.4 (16.2)
13	556	4	266.5 (13.0)	218.2 (3.4)	190.7 (7.0)	154.5 (10.1)

TABLE B.7. SOLUBLE CHEMICAL OXYGEN DEMAND CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	--	--	--	--	--	--
4	--	--	--	--	--	--
5	--	--	--	--	--	--
6	--	--	--	--	--	--
7	--	--	--	--	--	--
8	--	--	--	--	--	--
9	--	--	--	--	--	--
10	--	--	--	--	--	--
11	94	3	167.0 (3.6)	107.7 (4.0)	92.3 (18.6)	56.0 (17.4)
12	272	5	203.2 (20.2)	182.0 (20.8)	156.0 (15.8)	128.0 (13.0)
13	395	4	189.5 (6.4)	169.2 (5.1)	142.5 (6.6)	126.0 (3.8)

TABLE B.8. SUSPENDED SOLIDS DEMAND CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	117	5	90.2 (20.5)	15.8 (11.6)	--	--
4	73	3	78.3 (14.2)	30.1 (21.7)	--	--
5	68	3	77.7 (18.0)	32.0 (31.3)	--	--
6	47	3	111. (93.8)	26.2 (19.8)	--	--
7	206	1	140.0	36.2	--	--
8	46	20	97.2 (93.3)	33.8 (16.2)	--	--
9	110	13	108.9 (85.1)	33.5 (19.2)	--	--
10	175	3	62.5 (50.2)	4.3 (0.3)	--	--
11	20	3	35.1 (9.4)	27.1 (5.1)	17.2 (2.3)	4.1 (1.5)
12	57	5	42.4 (12.9)	31.7 (14.7)	17.3 (3.9)	7.3 (1.6)
13	98	4	47.2 (7.4)	24.1 (2.9)	26.2 (4.8)	16.4 (3.5)

TABLE B.9. VOLATILE SUSPENDED SOLIDS DEMAND CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	54	4	42.0 (39.1)	10.7 (10.2)	--	--
4	65	3	69.7 (13.0)	15.9 (1.7)	--	--
5	46	3	52.7 (24.9)	15.6 (4.4)	--	--
6	35	3	83.1 (63.6)	17.5 (7.8)	--	--
7	180	1	122.0	20.8	--	--
8	29	6	59.9 (81.2)	19.0 (7.8)	--	--
9	108	4	107.5 (34.8)	14.2 (12.4)	--	--
10	174	3	62.3 (22.8)	2.9 (0.1)	--	--
11	24	4	42.3 (17.6)	24.4 (4.7)	--	--
		3			15.3 (2.2)	3.8 (1.2)
12	50	5	37.4 (11.7)	26.7 (11.8)	15.8 (3.5)	6.8 (1.3)
13	87	4	41.8 (6.1)	20.4 (2.2)	23.4 (4.1)	15.5 (3.1)

TABLE B.10. TOTAL KJELDAHL NITROGEN CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	--	--	--	--	--	--
4	44.5	1	47.4	40.2	--	--
5	41.2	3	47.0 (2.2)	39.2 (1.6)	--	--
6	20.2	3	48.3 (2.9)	31.8 (1.4)	--	--
7	67.9	2	46.1 (3.5)	36.6 (2.7)	--	--
8	17.5	13	36.7 (12.2)	27.3 (6.4)	--	--
9	27.3	5	27.1 (7.2)	22.6 (6.4)	--	--
10	--	--	--	--	--	--
11	13.0	3	23.1 (2.5)	21.8 (2.0)	20.5 (1.7)	16.9 (1.3)
12	36.4	6	27.2 (3.4)	25.7 (2.3)	23.1 (1.8)	20.4 (2.4)
13	44.4	5	21.3 (6.1)	19.6 (2.2)		
		6			18.6 (2.8)	18.8 (2.7)

TABLE B.11. NITRATE NITROGEN CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	1	0.0 --	16.8 --	--	--
2	--	--	--	--	--
3	2	0.0 --	0.4 (0.1)	--	--
4	3	0.0 --	4.2 (4.7)	--	--
5	4	0.0 --	0.4 (0.2)	--	--
6	3	0.0 --	2.9 (3.4)	--	--
7	3	0.0 --	0.9 (0.7)	--	--
8	13	0.0 --	4.1 (2.3)	--	--
9	5	0.0 --	1.4 (1.6)	--	--
10	--	--	--	--	--
11	4	0.0 --	0.0 --	0.0 --	0.26 (0.21)
12	6	0.0 --	0.0 --	0.0 --	0.0 --
13	5	0.0 --	0.0 --	0.0 --	-- --
	8	-- --	-- --	-- --	0.0 --

TABLE B.12. AMMONIUM NITROGEN CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	1	55.3 --	23.0 --	--	--
2	--	--	--	--	--
3	2	40.0 (4.9)	36.6 (3.7)	--	--
4	3	36.2 (2.3)	30.1 (3.8)	--	--
5	4	37.8 (3.3)	32.8 (1.5)	--	--
6	3	35.3 (1.9)	25.2 (3.7)	--	--
7	2	35.3 (3.0)	29.9 (3.0)	--	--
8	13	29.0 (9.1)	19.8 (6.9)	--	--
9	5	21.6 (4.7)	18.1 (6.3)	--	--
10	--	--	--	--	--
11	4	21.4 (2.7)	20.2 (3.0)	20.5 (3.4)	17.5 (2.9)
12	6	21.8 (2.2)	21.8 (2.6)	21.5 (3.2)	21.7 (2.8)
13	5	20.7 (2.5)	21.3 (3.1)	20.0 (3.5)	21.3 (3.5)

TABLE B.13. TOTAL PHOSPHORUS CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--	--
2	--	--	--	--	--	--
3	--	--	--	--	--	--
4	7.22	1	7.7	7.3	--	--
5	6.31	3	7.2 (0.5)	5.8 (1.2)	--	--
6	3.77	3	9.0 (0.9)	6.1 (1.1)	--	--
7	12.96	2	8.8 (0.1)	7.6 (1.1)	--	--
8	3.05	12	6.4 (2.3)	5.1 (1.2)	--	--
9	1.24	5	4.8 (1.6)	4.7 (1.1)	--	--
10	--	--	--	--	--	--
11	2.97	4	5.3 (0.1)	5.0 (0.2)	4.7 (0.5)	4.1 (0.7)
12	7.62	4	5.7 (0.5)	5.4 (0.6)	5.2 (0.6)	4.8 (0.7)
13	44.4	5	5.8 (0.5)	5.6 (0.6)	5.5 (0.7)	5.5 (0.8)

TABLE B.14. SOLUBLE PHOSPHORUS CONCENTRATIONS (mg/ℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--
2	--	--	--	--	--
3	3	6.5 (0.1)	6.1 (0.5)	--	--
4	1	9.3 --	6.5 --	--	--
5	3	7.7 (0.7)	8.0 (0.4)	--	--
6	--	--	--	--	--
7	--	--	--	--	--
8	13	4.8 (1.5)	4.3 (1.1)	--	--
9	5	4.1 (1.0)	4.4 (1.0)	--	--
10	--	--	--	--	--
11	4	4.6 (0.3)	4.4 (0.2)	4.2 (0.5)	3.8 (0.9)
12	6	4.7 (0.5)	4.7 (0.5)	4.6 (0.6)	4.6 (0.7)
13	5	4.5 (0.4)	4.7 (0.5)	4.7 (0.6)	4.8 (0.7)

TABLE B.15. pH IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of pH Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	2	8.0 (0.8)	7.7 (0.4)	--	--
2	--	--	--	--	--
3	7	7.3 (0.2)	7.3 (0.1)	--	--
4	3	7.3 (0.2)	7.2 (0.2)	--	--
5	6	7.3 (0.2)	7.2 (0.1)	--	--
6	4	7.1 (0.2)	7.0 (0.1)	--	--
7	3	7.3 (0.2)	7.1 (0.1)	--	--
8	37	7.2 (0.4)	6.9 (0.3)	--	--
9	28	6.9 (0.3)	6.9 (0.2)	--	--
10	6	7.2 (1.2)	7.1 (1.1)	--	--
11	4	7.2 (0.6)	7.4 (0.1)	7.3 (0.1)	-- --
	3				7.4 (0.1)
12	--	--	--	--	--
13	--	--	--	--	--

TABLE B.16. FECAL COLIFORMS CONCENTRATIONS (NUMBER/100 mℓ) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of pH Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--
2	--	--	--	--	--
3	1	0.9	0.4	--	--
4	1	1.6	0.0	--	--
5	1	1.8	0.8	--	--
6	1	2.1	0.7	--	--
7	--	--	--	--	--
8	4	7.9 (2.8)	0.6 (0.2)	--	--
9	4	6.0 (1.6)	1.4 (1.5)	--	--
10	1	3.6	1.0	--	--
11	--	--	--	--	--
12	--	--	--	--	--
13	--	--	--	--	--

TABLE B.17. TURBIDITY (JTU) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of pH Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	1	58.0	27.0	--	--
2	--	--	--	--	--
3	7	48.7 (13.7)	13.5 (9.9)	--	--
4	3	38.0 (4.0)	17.0 (2.0)	--	--
5	6	40.7 (4.8)	18.7 (1.6)	--	--
6	4	51.0 (16.9)	13.6 (3.2)	--	--
7	2	49.5 (9.2)	25.5 (3.5)	--	--
8	37	44.8 (18.0)	13.2 (6.3)	--	--
9	28	51.8 (34.3)	14.8 (8.8)	--	--
10	6	28.8 (12.1)	5.6 (6.1)	--	--
11	--	--	--	--	--
12	--	--	--	--	--
13	--	--	--	--	--

TABLE B.18. SEWAGE TEMPERATURE (°C) IN PILOT SCALE SYSTEMS TREATING DOMESTIC SEWAGE IN NEW HAMPSHIRE. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of pH Determinations	Unit 1 Influent	Unit 1 Effluent	Unit 2 Effluent	Unit 3 Effluent
1	--	--	--	--	--
2	3	10.3 (0.6)	13.5 (1.8)	--	--
3	3	10.7 (0.6)	15.0 (1.7)	--	--
4	5	9.1 (0.7)	14.2 (2.0)	--	--
5	4	7.6 (2.4)	12.8 (0.5)	--	--
6	3	8.8 (0.3)	12.0 (1.0)	--	--
7	--	--	--	--	--
8	37	9.2 (0.9)	13.8 (2.1)	--	--
9	27	12.2 (1.5)	15.5 (1.5)	--	--
10	6	16.0 (1.2)	17.2 (0.4)	--	--
11	5	14.0 (0.7)	24.0 (3.6)	25.8 (4.8)	24.8 (6.0)
12	7	16.0 (2.7)	21.4 (4.5)	23.0 (4.8)	20.7 (3.8)
13	9	18.2 (1.9)	21.8 (2.2)	22.6 (2.6)	21.5 (2.8)

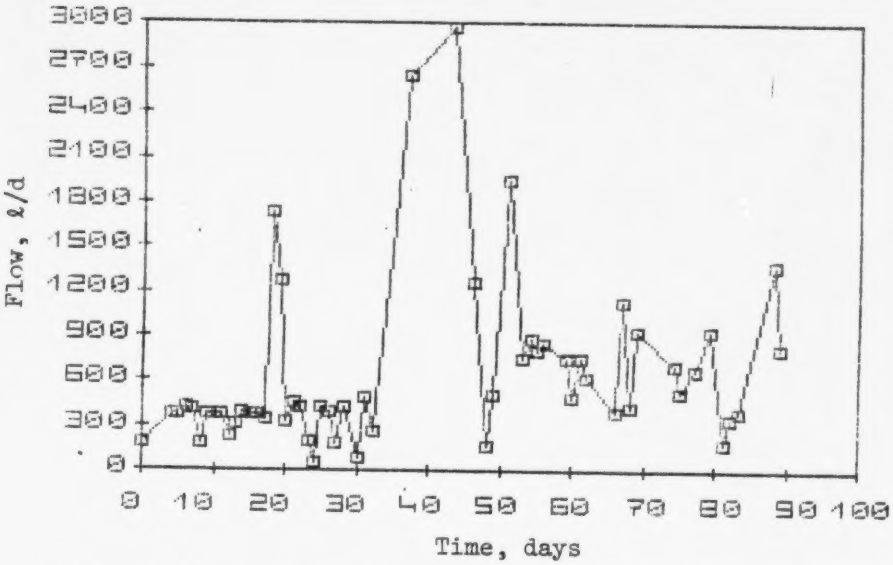


Figure B.1. Daily influent sewage flow to the CRREL NFT unit in Phase 0, beginning on November 16, 1979.

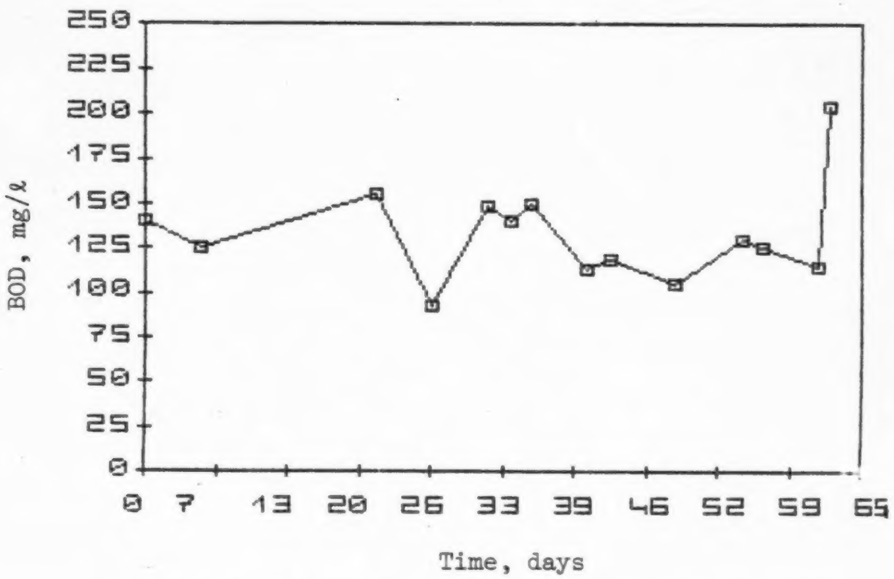


Figure B.2. Biochemical oxygen demand concentration of influent sewage flow to the CRREL NFT unit in Phase 0. First day of analysis was December 7, 1979.

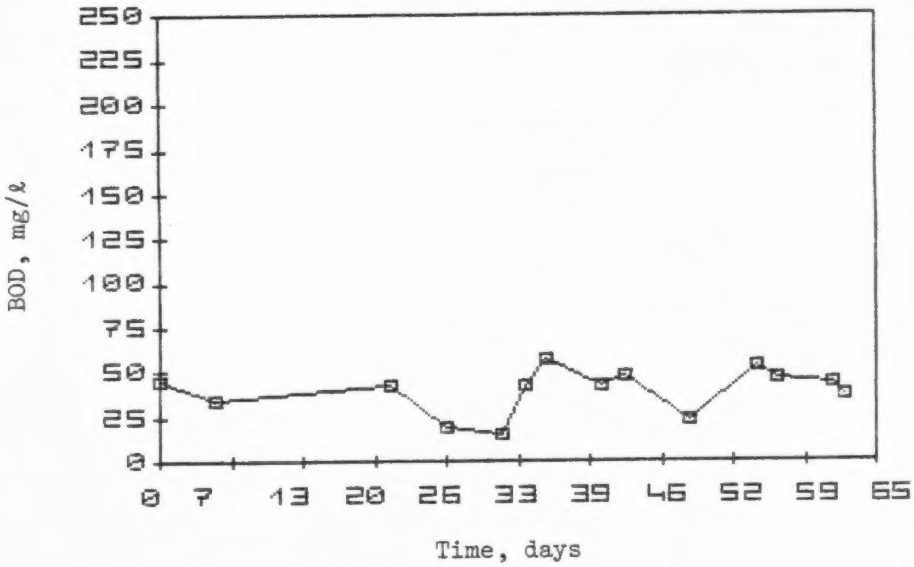


Figure B.3. Biochemical oxygen demand concentration of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was December 7, 1979.

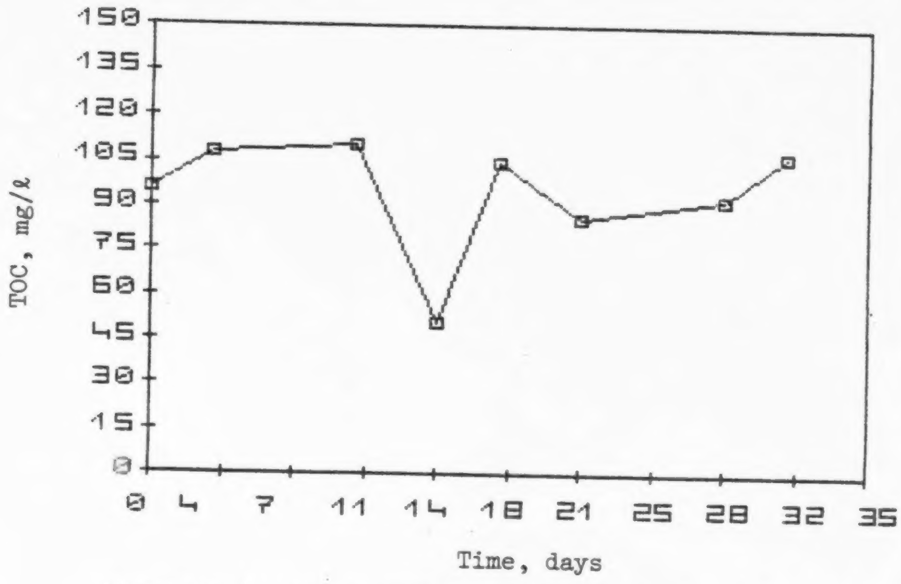


Figure B.4. Total organic carbon concentration of influent sewage flow to the CRREL NFT unit in Phase 0. First day of analysis was January 2, 1980.

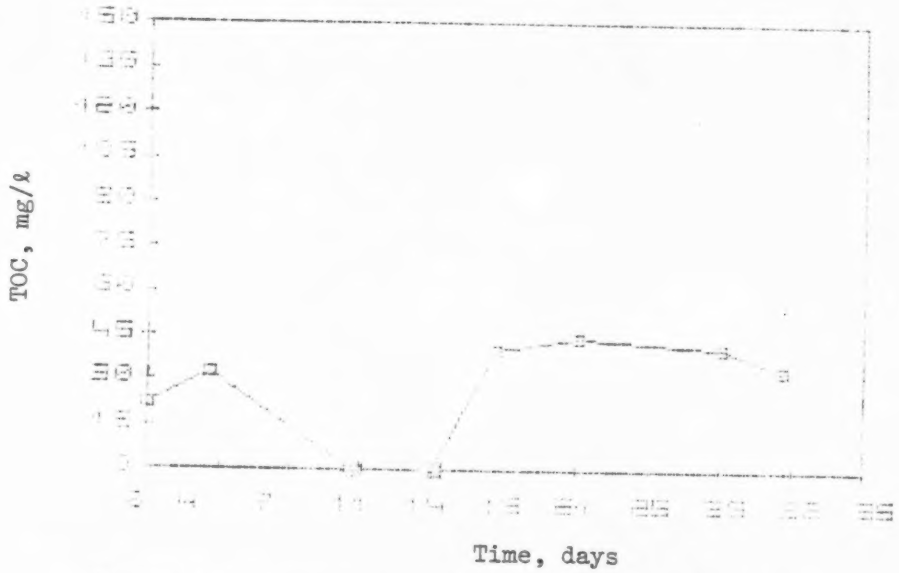


Figure B.5. Total organic carbon concentration of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was January 2, 1980.

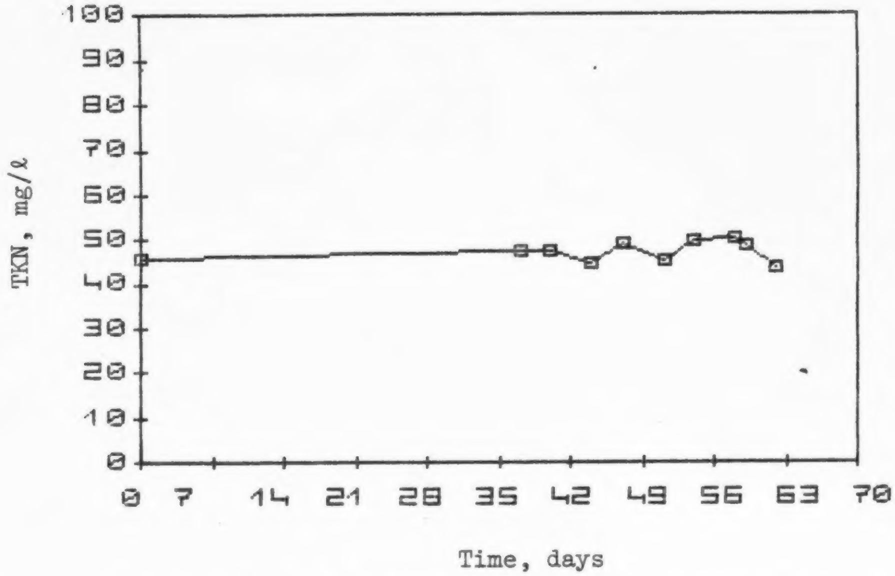


Figure B.6. Total Kjeldahl nitrogen concentration of influent sewage flow to the CRREL NFT unit in Phase 0. First day of analysis was December 12, 1979.

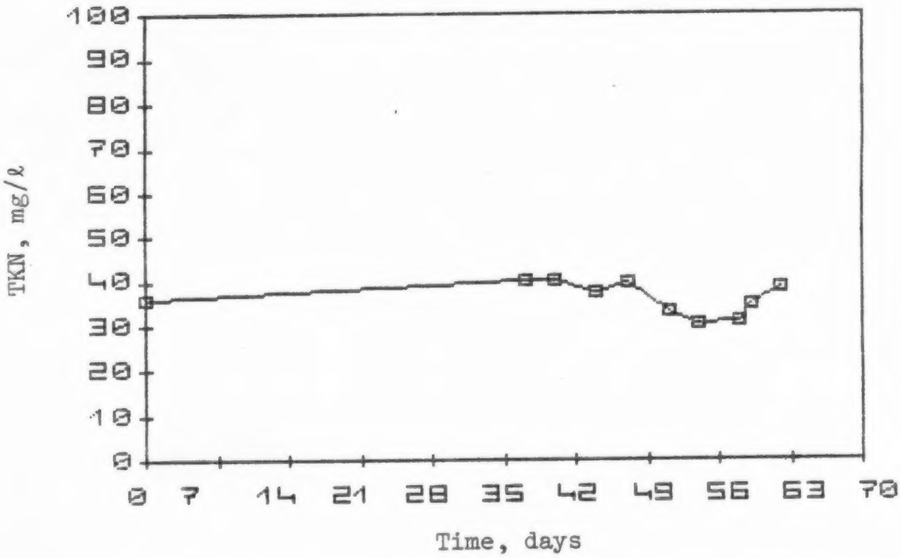
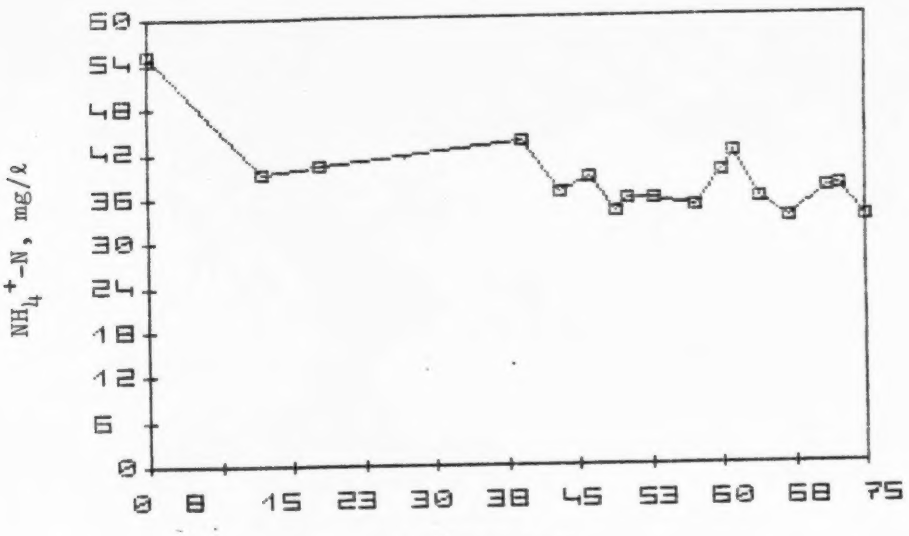
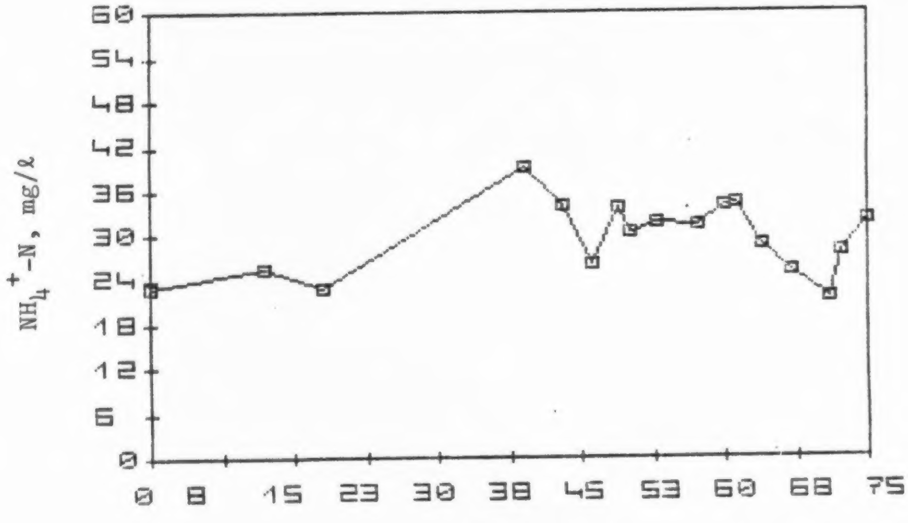


Figure B.7. Total Kjeldahl nitrogen concentration of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was December 12, 1979.



Time, days

Figure B.8. Ammonium nitrogen concentration of influent sewage flow to the CRREL NFT unit in Phase 0. First day of analysis was November 29, 1979.



Time, days

Figure B.9. Ammonium nitrogen concentration of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was November 29, 1979.

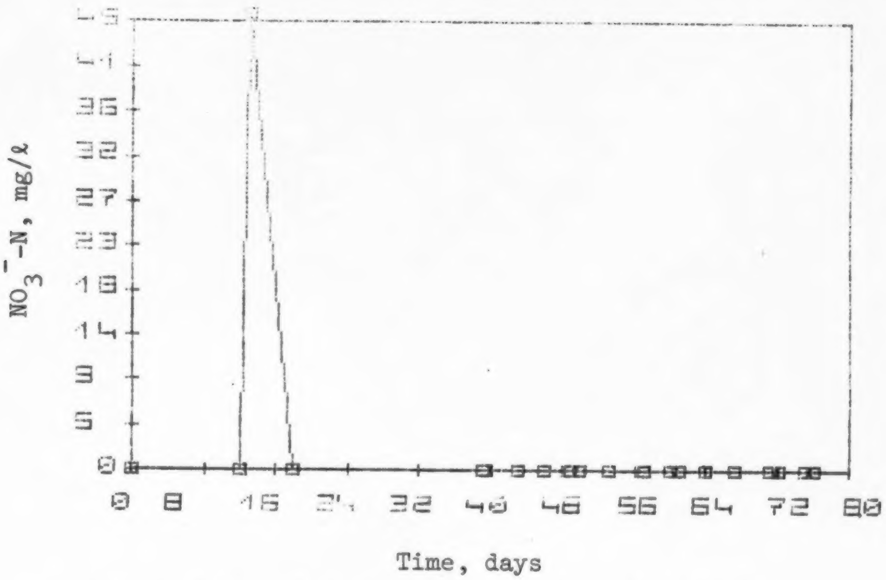


Figure B.10. Nitrate concentration of influent sewage flow to the CRREL NFT unit in Phase 0. First day of analysis was November 29, 1979.

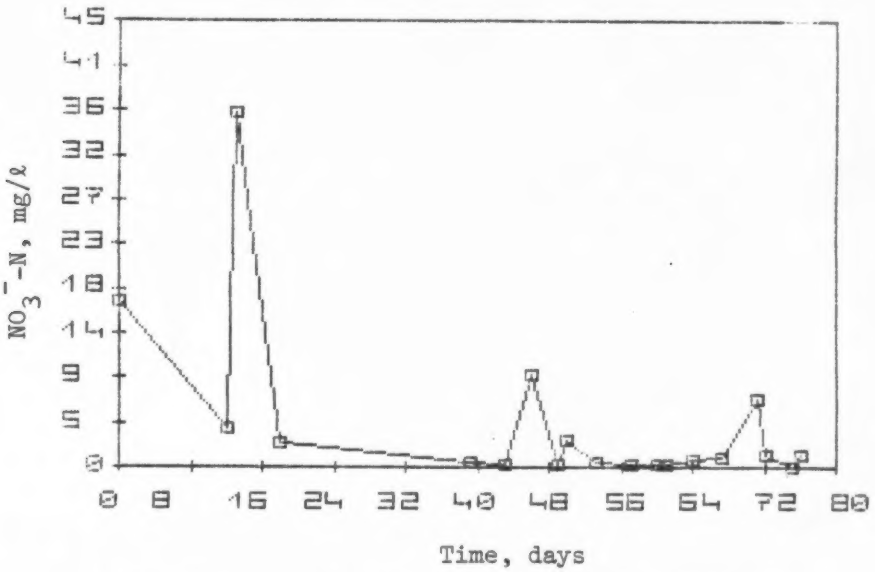


Figure B.11. Nitrate nitrogen concentration of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was November 29, 1979.

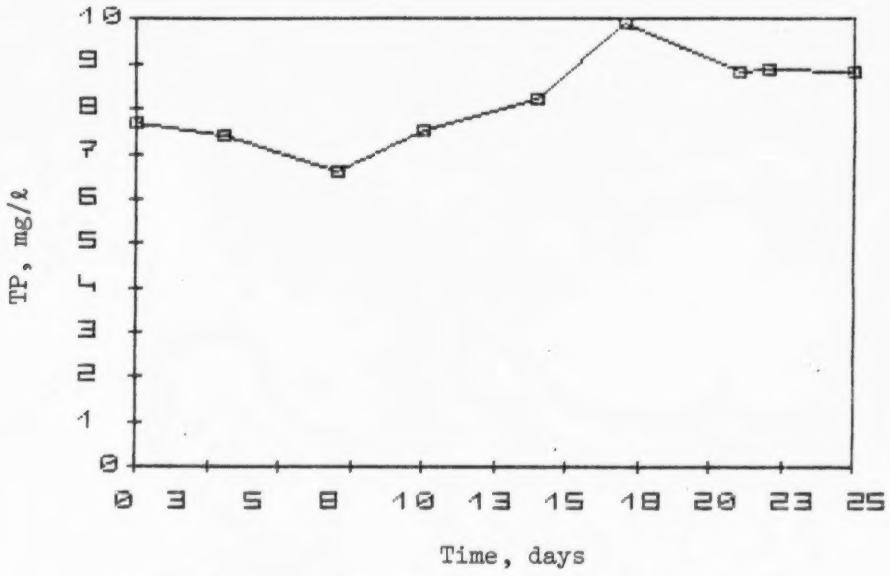


Figure B.12. Total phosphorus concentration of influent sewage to the CRREL unit in Phase 0. First day of analysis was January 18, 1980.

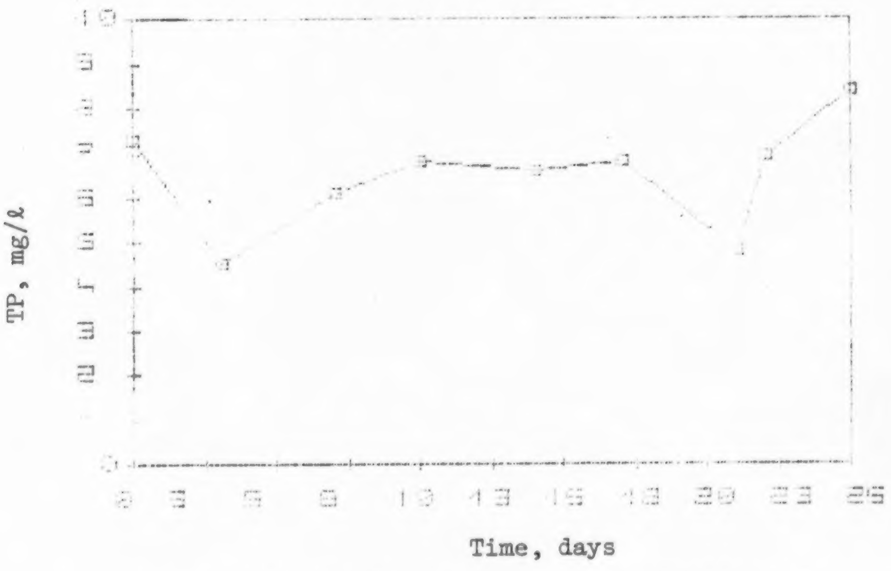


Figure B.13. Total phosphorus concentration of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was January 18, 1980.

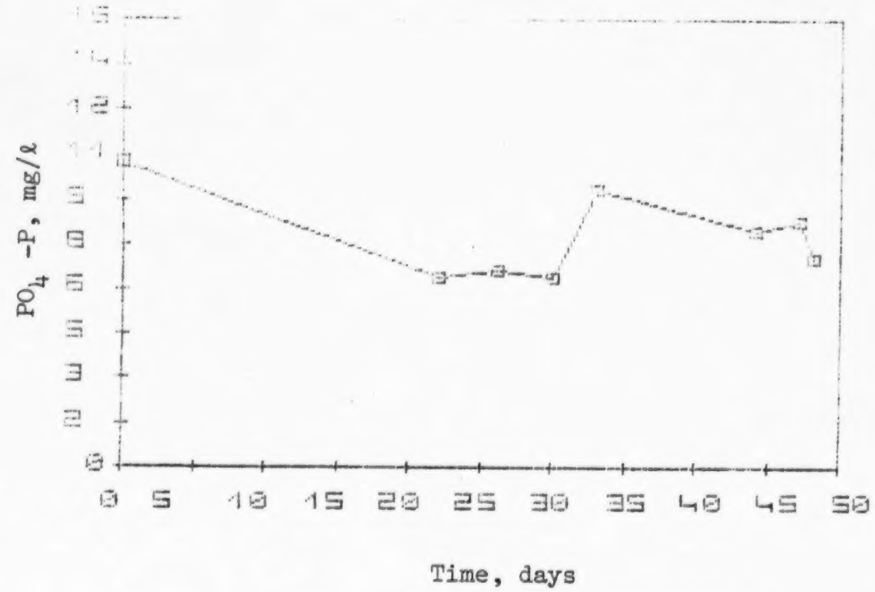


Figure B.14. Orthophosphate concentration of influent sewage to the CRREL NFT unit in Phase 0. First day of analysis was December 12, 1979.

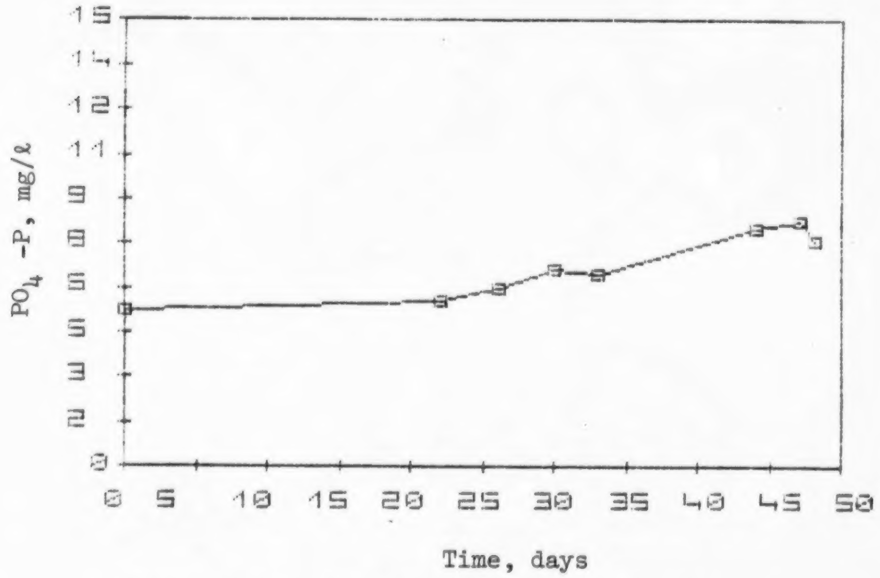


Figure B.15. Orthophosphate concentration of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was December 12, 1979.

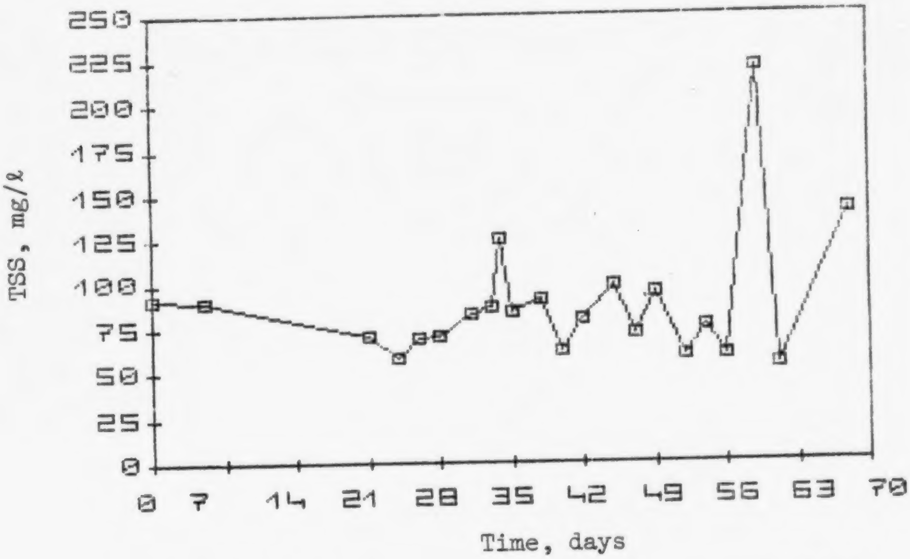


Figure B.16. Total suspended solids concentration of influent sewage to the CRREL NFT unit in Phase 0. First day of analysis was December 7, 1979.

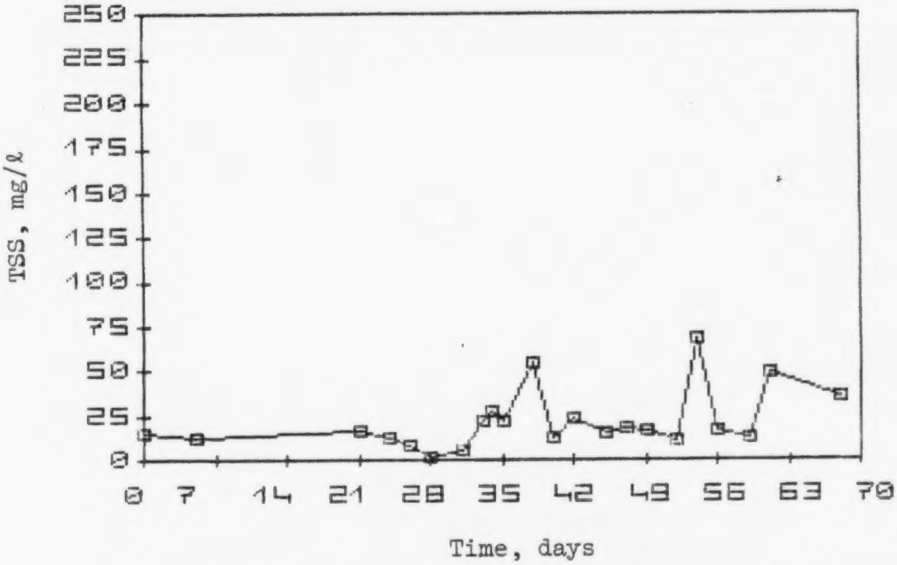


Figure B.17. Total suspended solids concentration of the effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was December 7, 1979.

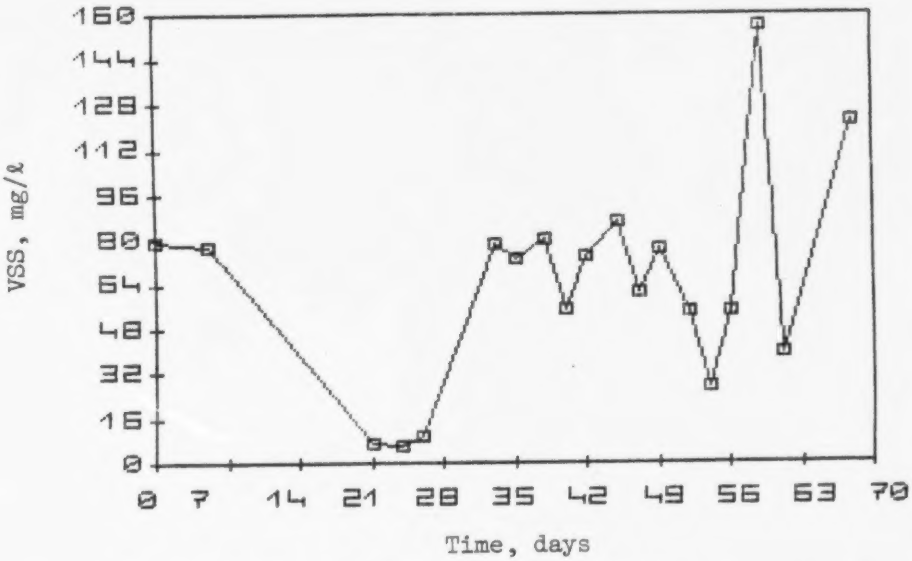


Figure B.18. Volatile suspended solids concentration of influent sewage to the CRREL NFT unit in Phase 0. First day of analysis was December 7, 1979.

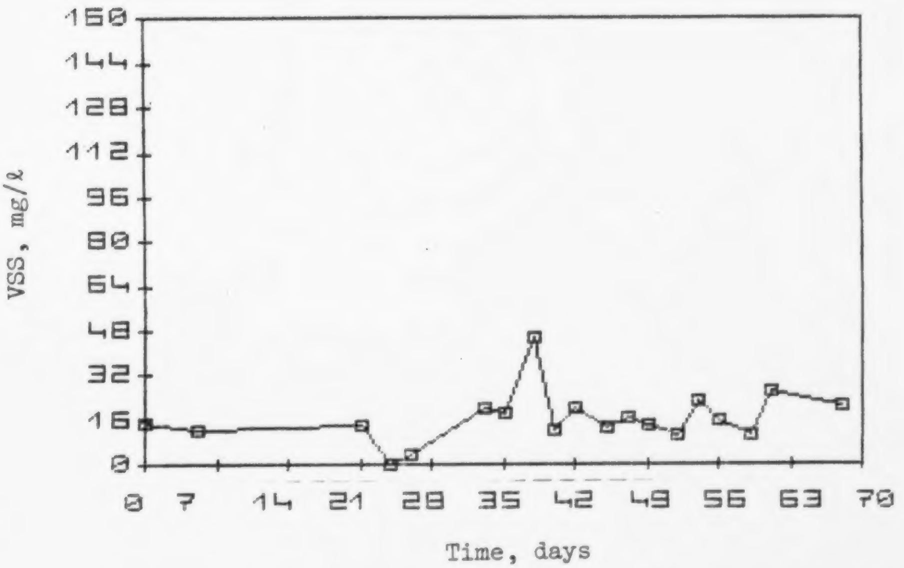


Figure B.19. Volatile supsended solids concentration of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was December 7, 1979.

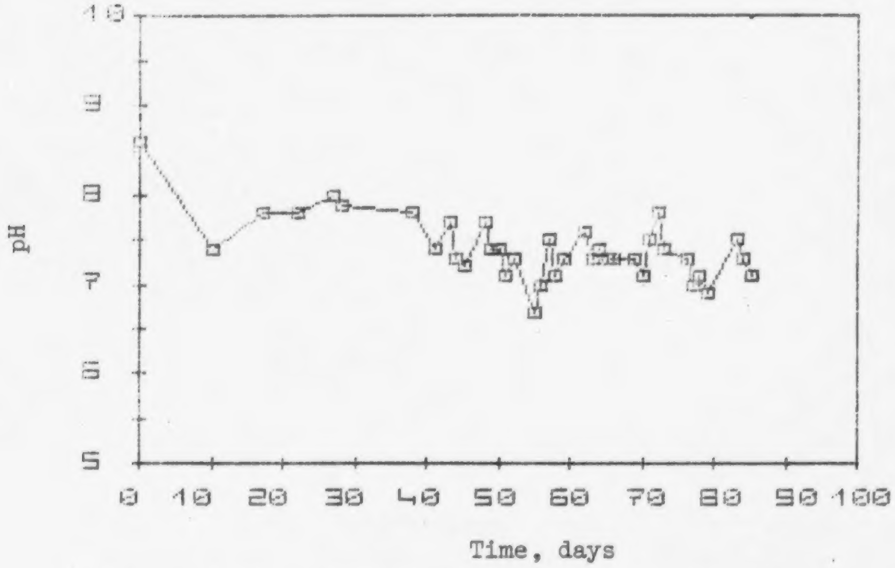


Figure B.20. pH of influent sewage to the CRREL NFT unit in Phase 0. First day of analysis was November 20, 1979.

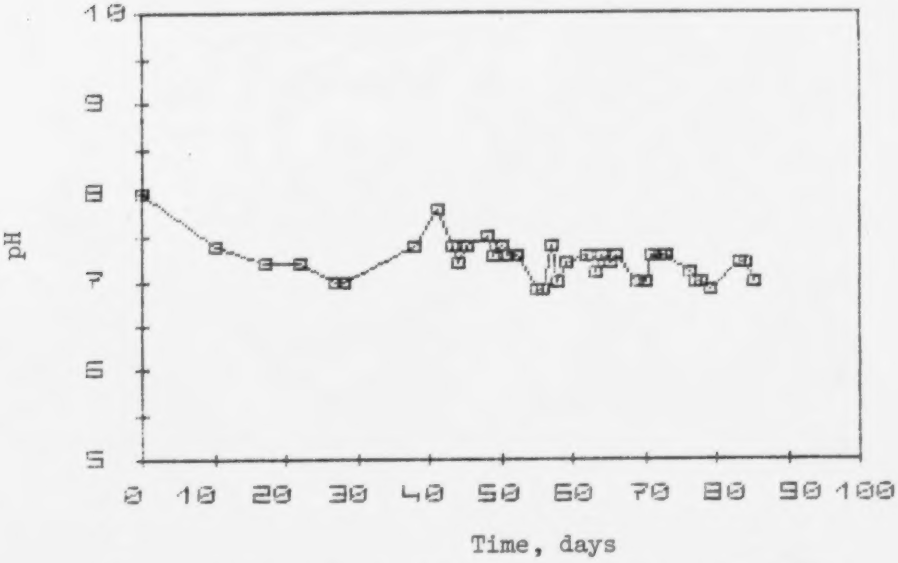


Figure B.21. pH of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was November 20, 1979.

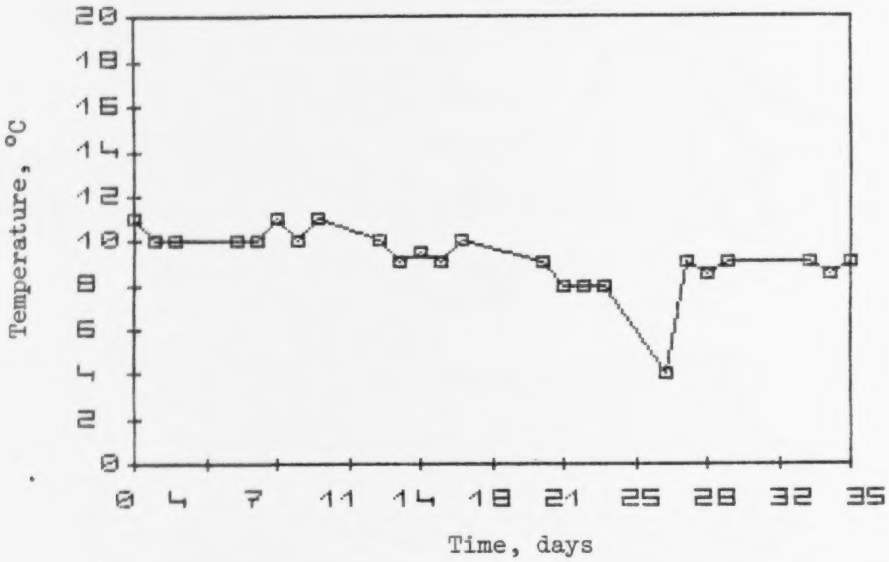


Figure B.22. Temperature of influent sewage to the CRREL NFT unit in Phase 0. First day of analysis was November 30, 1979.

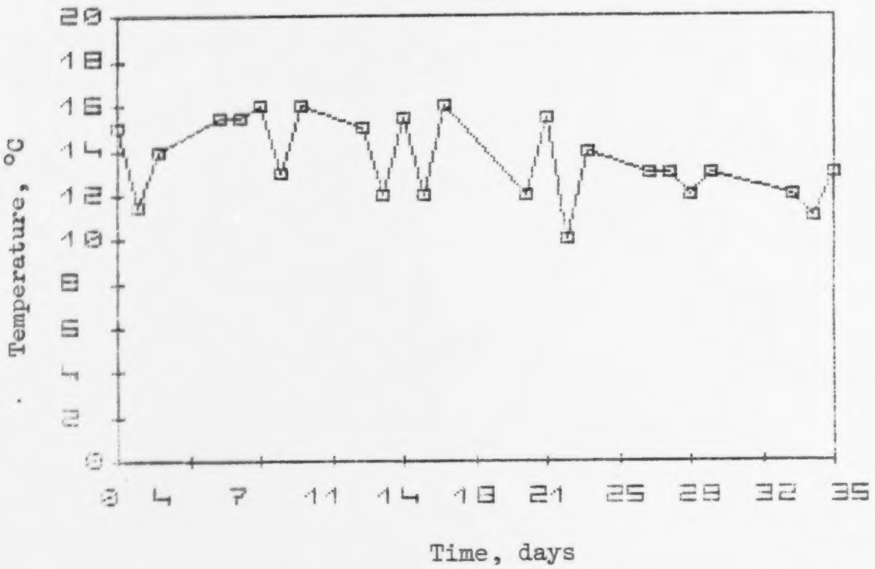


Figure B.23. Temperature of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was November 30, 1979.

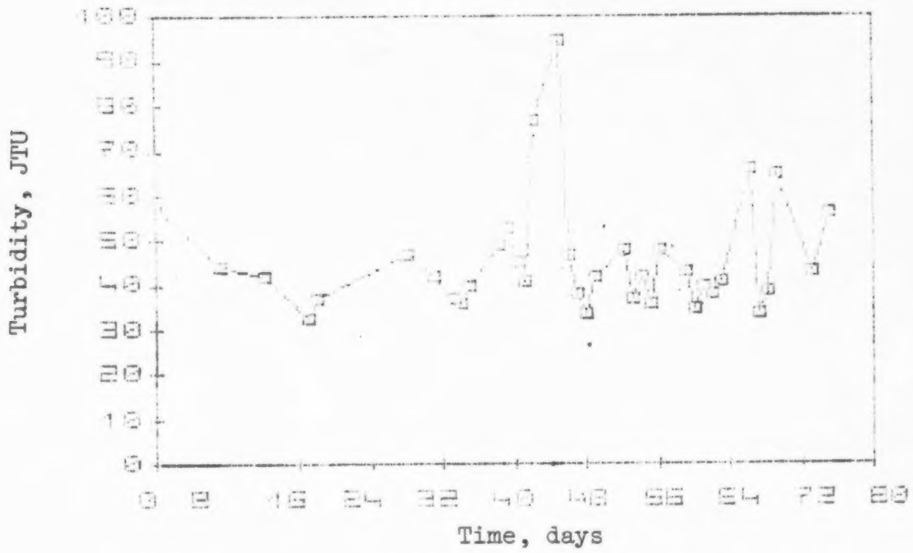


Figure B.24. Turbidity of influent sewage to the CRREL NFT unit in Phase 0. First day of analysis was November 30, 1979.

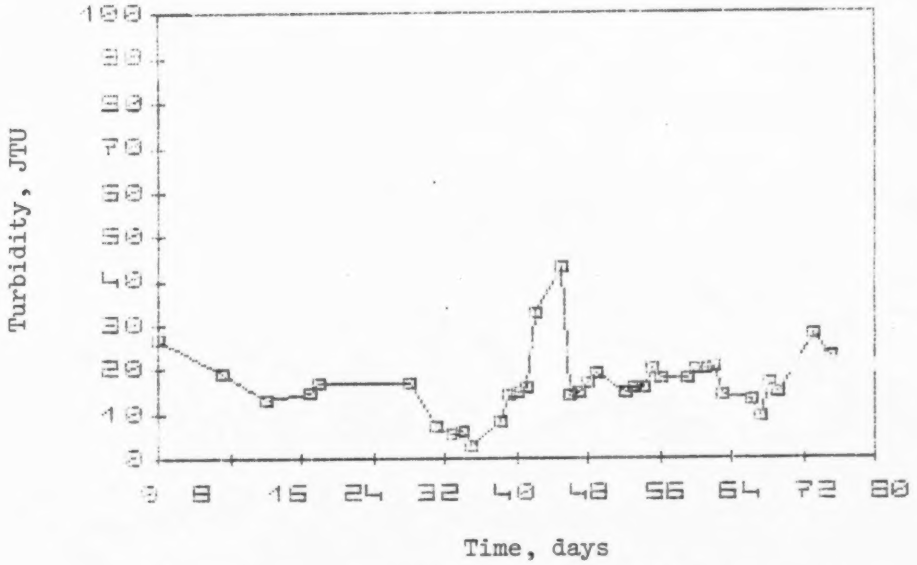


Figure B.25. Turbidity of effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was November 30, 1979.

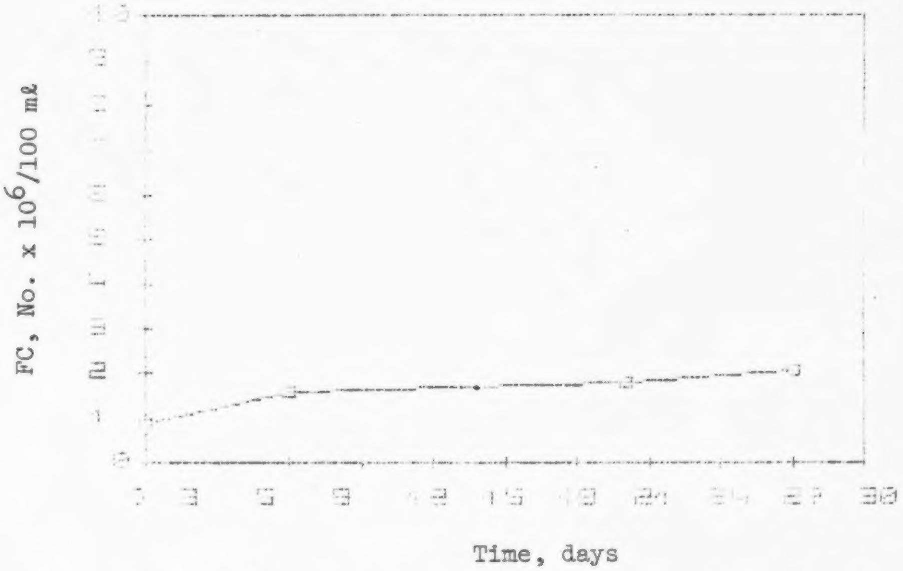


Figure B.26. Numbers of fecal coliforms in influent sewage to the CRREL NFT unit in Phase 0. First day of analysis was January 9, 1980.

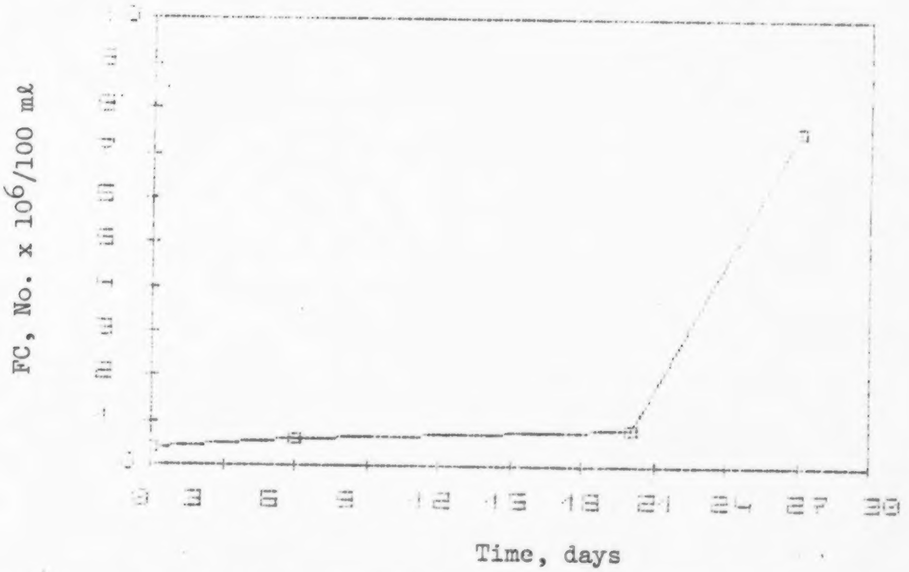


Figure B.27. Numbers of fecal coliforms in effluent sewage from the CRREL NFT unit in Phase 0. First day of analysis was January 9, 1979.

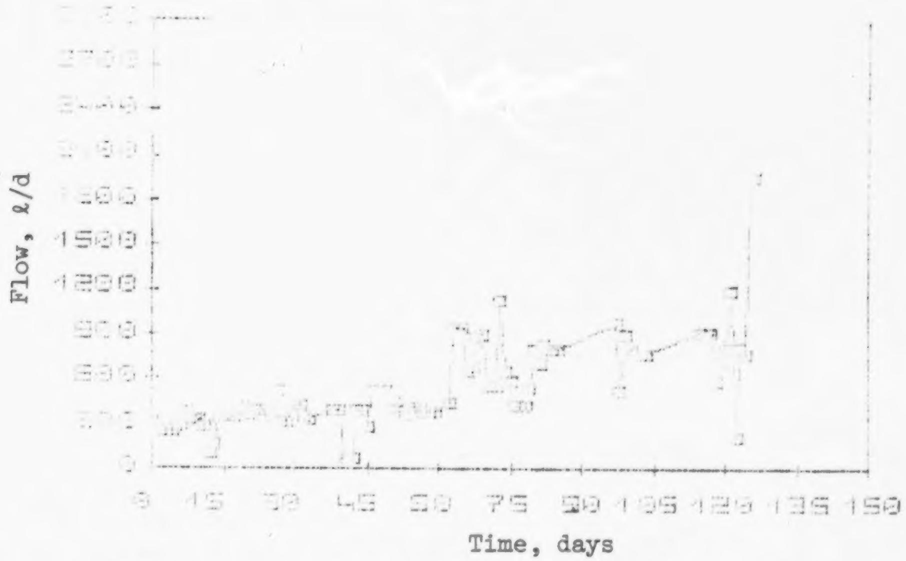


Figure B.28. Daily influent sewage flow to the CRREL NFT unit in Phase 1, beginnong on February 15, 1980.

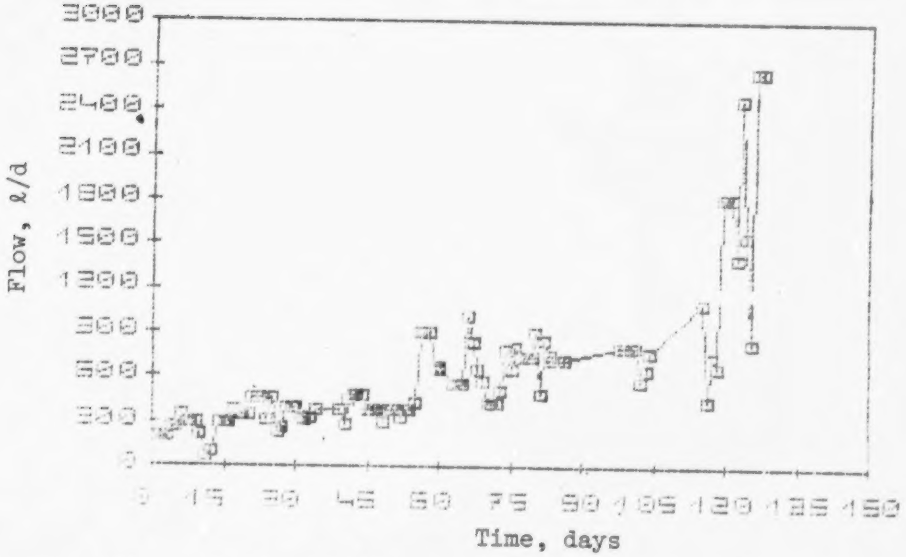


Figure B.29. Daily effluent sewage flow from the CRREL NFT unit in Phase 1, beginning on February 16, 1980.

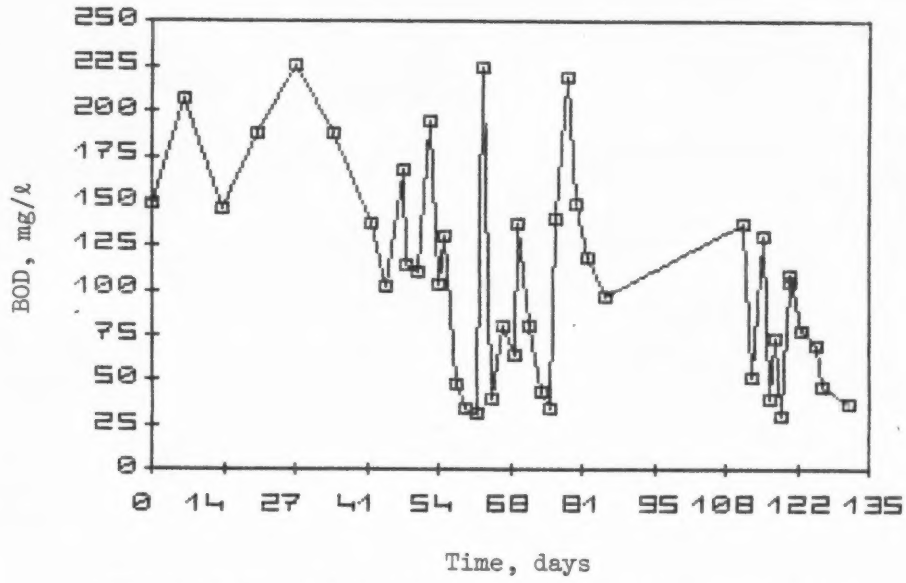


Figure B.30. Biological oxygen demand concentrations of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

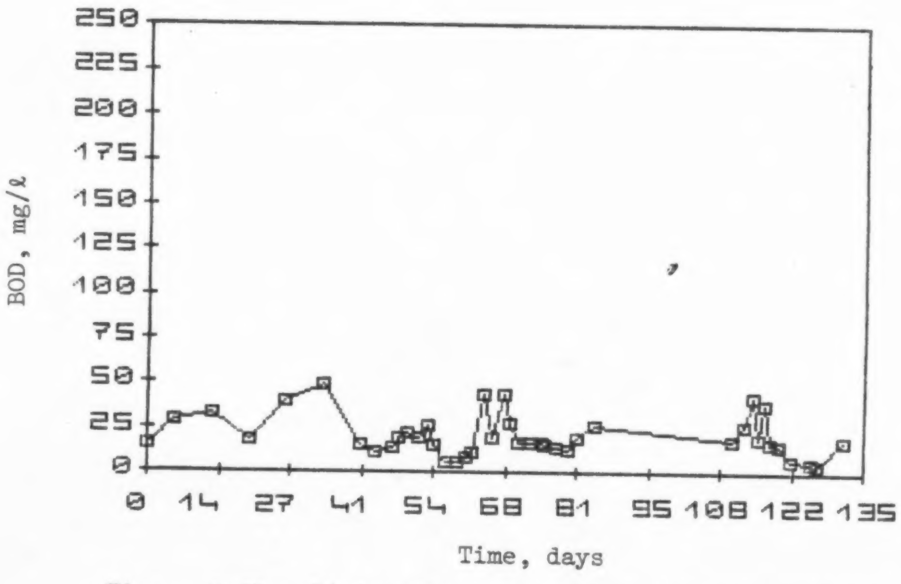


Figure B.31. Biological oxygen demand concentrations of effluent sewage from the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

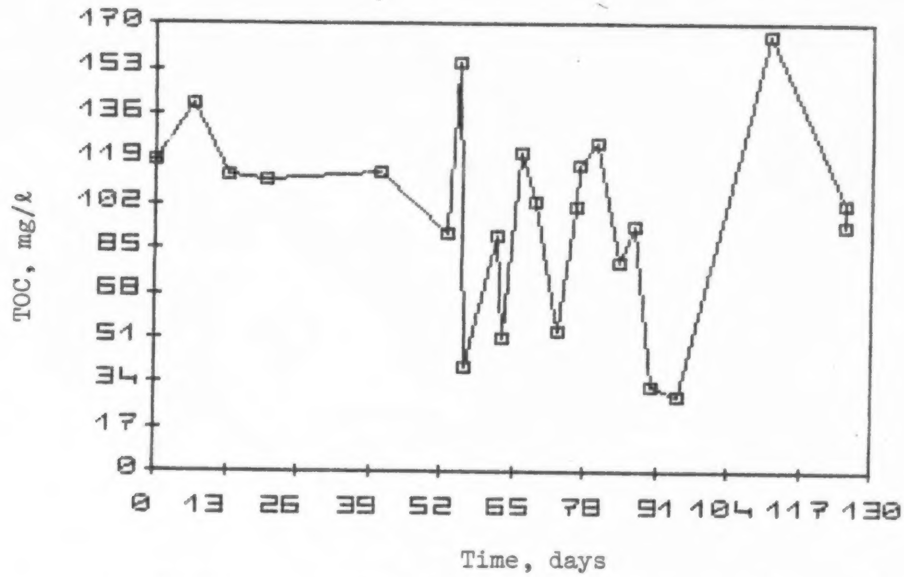


Figure B.32. Total organic carbon concentrations of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

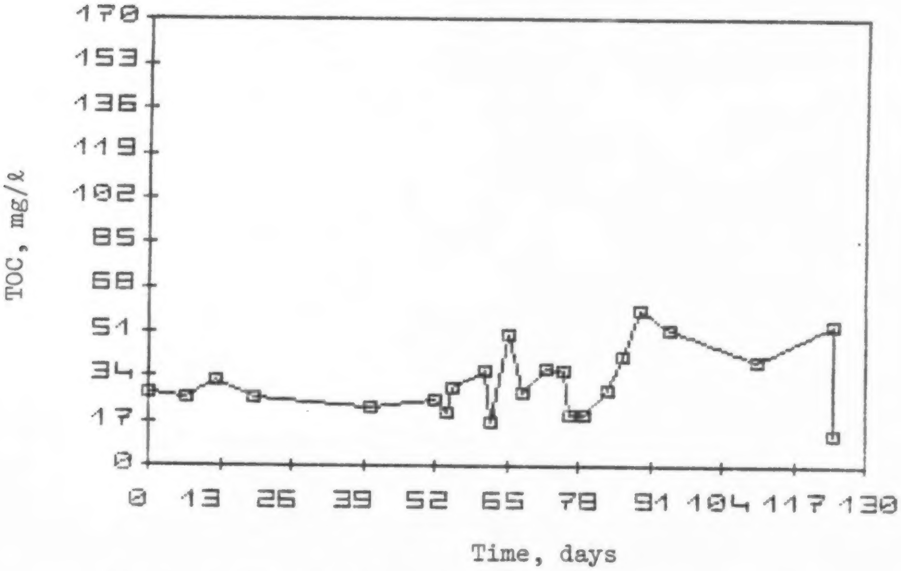


Figure B.33. Total organic carbon concentrations of effluent sewage from the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

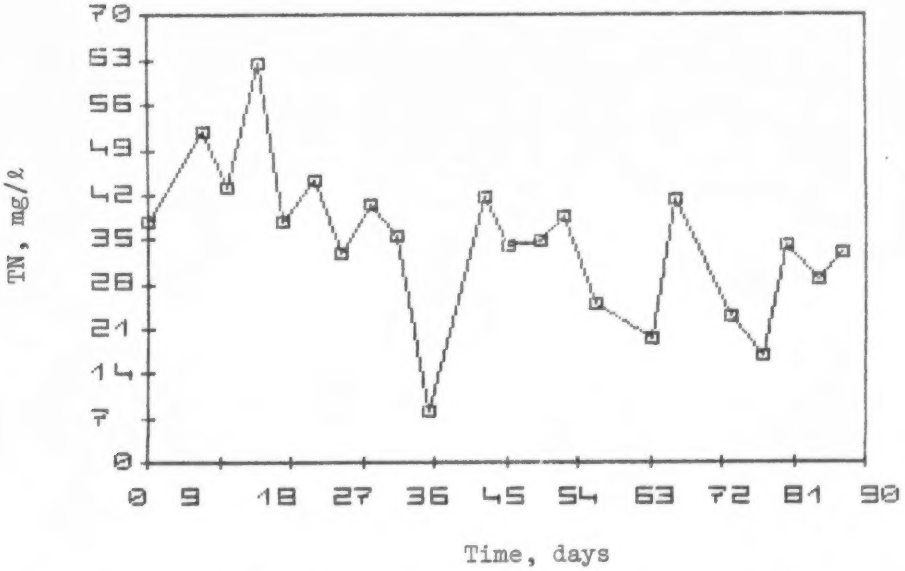


Figure B.34. Total nitrogen concentrations of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

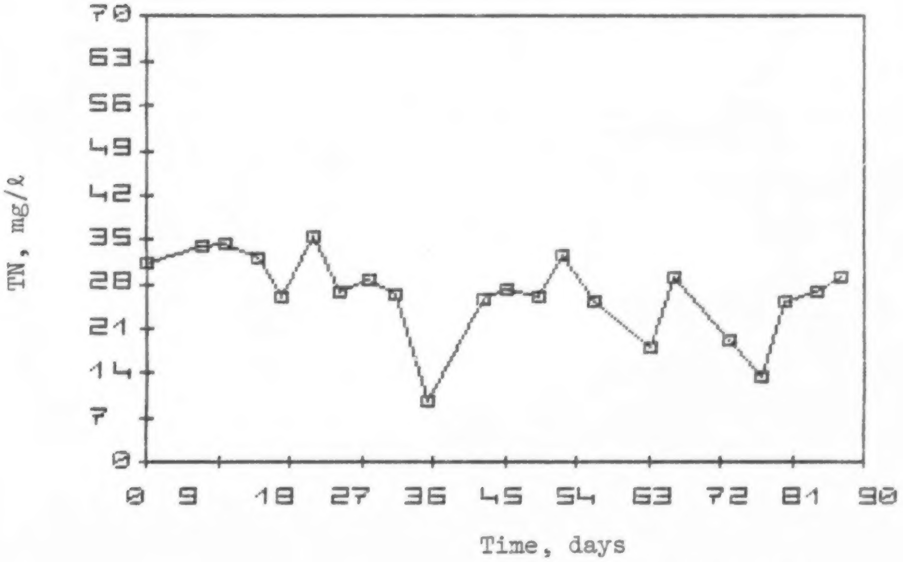


Figure B.35. Total nitrogen concentrations of effluent sewage from the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

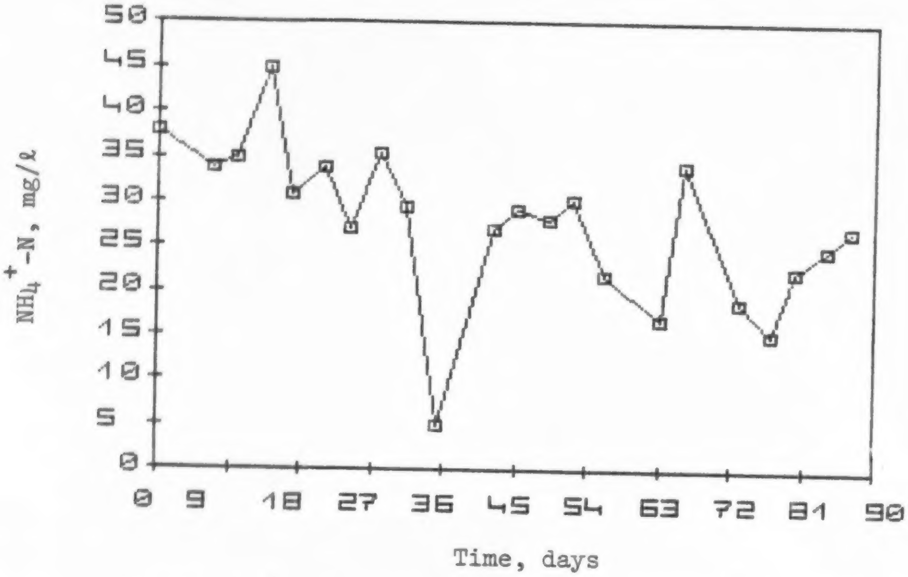


Figure B.36. Ammonium nitrogen concentrations of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

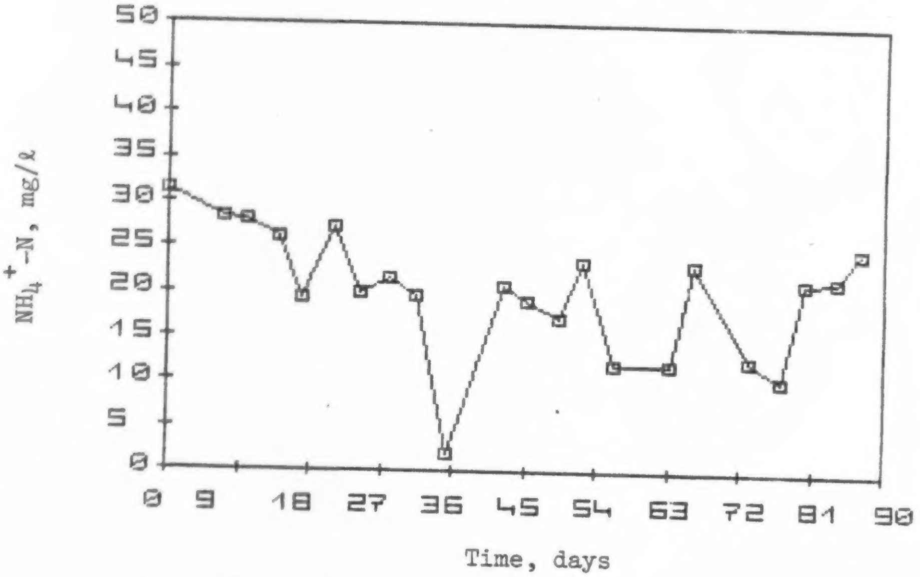


Figure B.37. Ammonium nitrogen concentrations of effluent sewage from the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

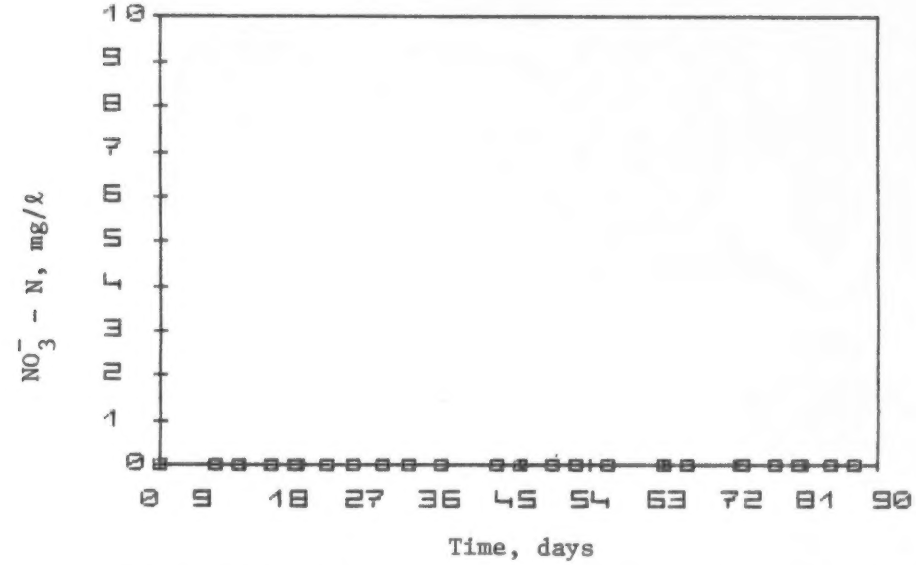


Figure B.38. Nitrate nitrogen concentrations of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

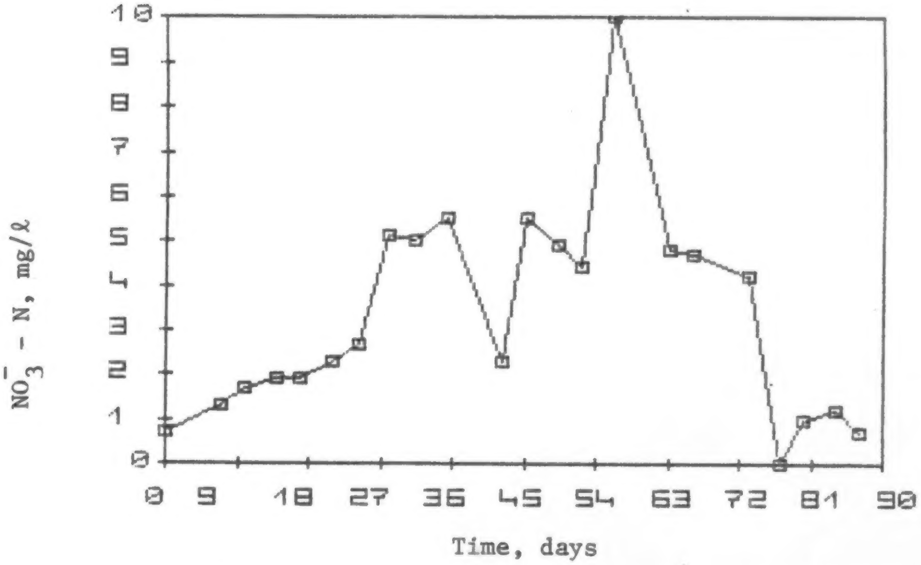


Figure B.39. Nitrate nitrogen concentrations of effluent sewage from the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

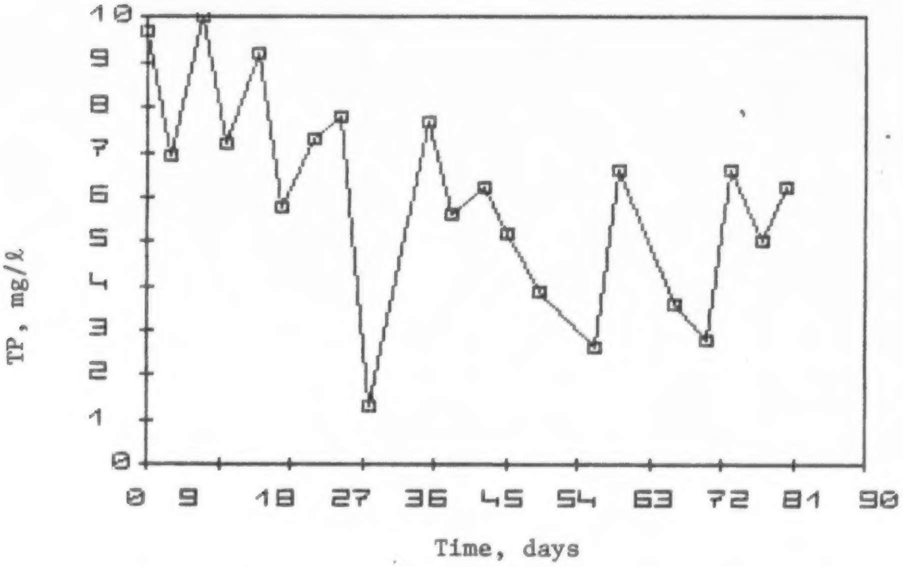


Figure B.40. Total phosphorus concentration of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 22, 1980.

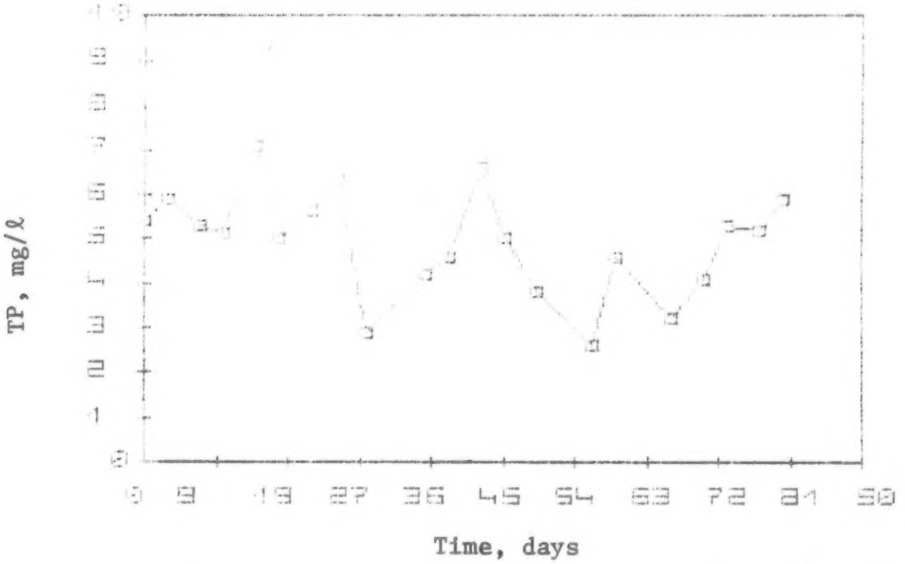


Figure B.41. Total phosphorus concentration of influent sewage from CRREL NFT unit in Phase 1. First day of analysis was February 22, 1980.

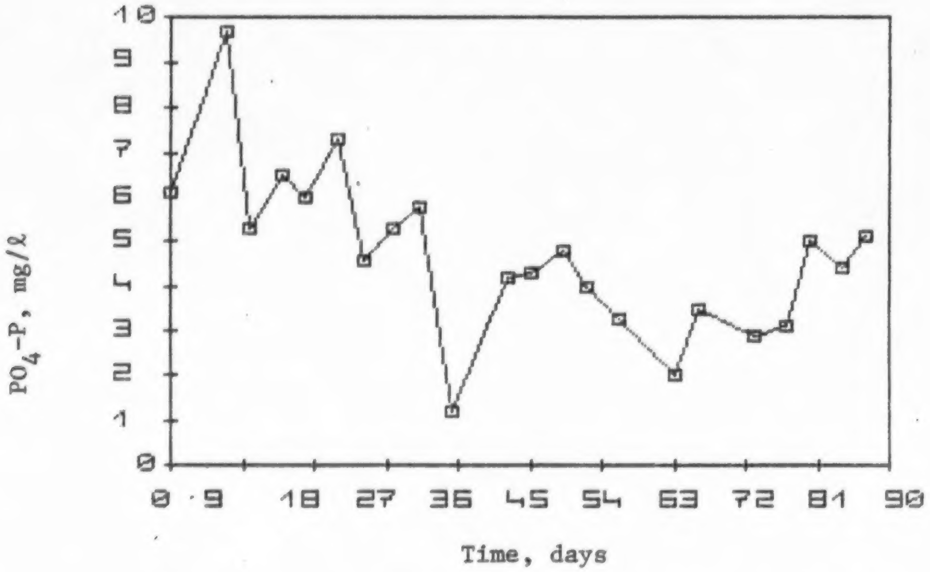


Figure B.42. Orthophosphate concentration of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

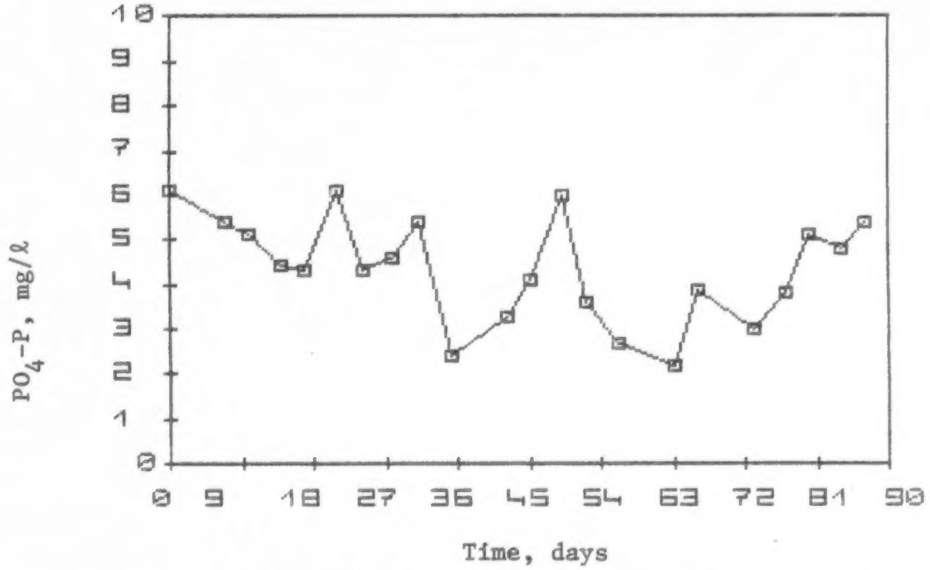


Figure B.43. Orthophosphate concentration of effluent from the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

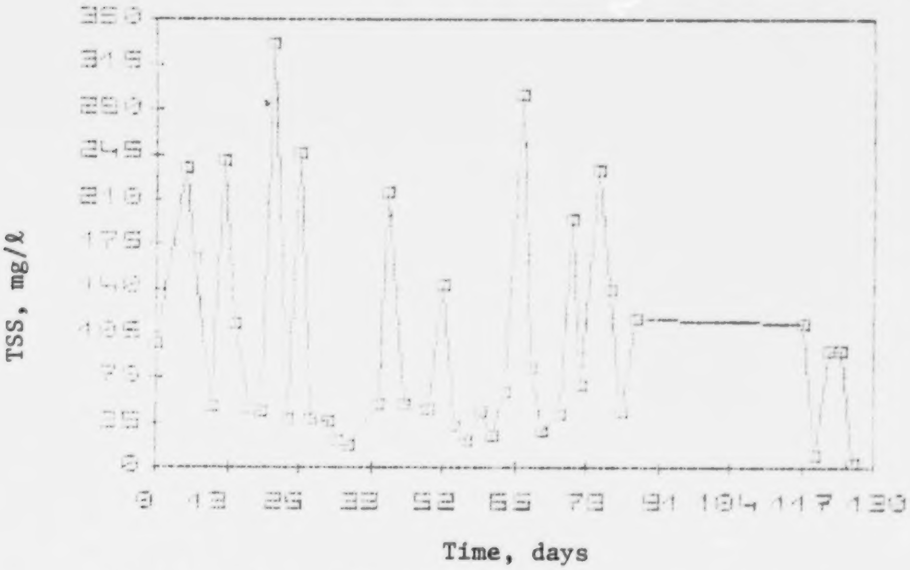


Figure B.44. Total suspended solids concentration of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

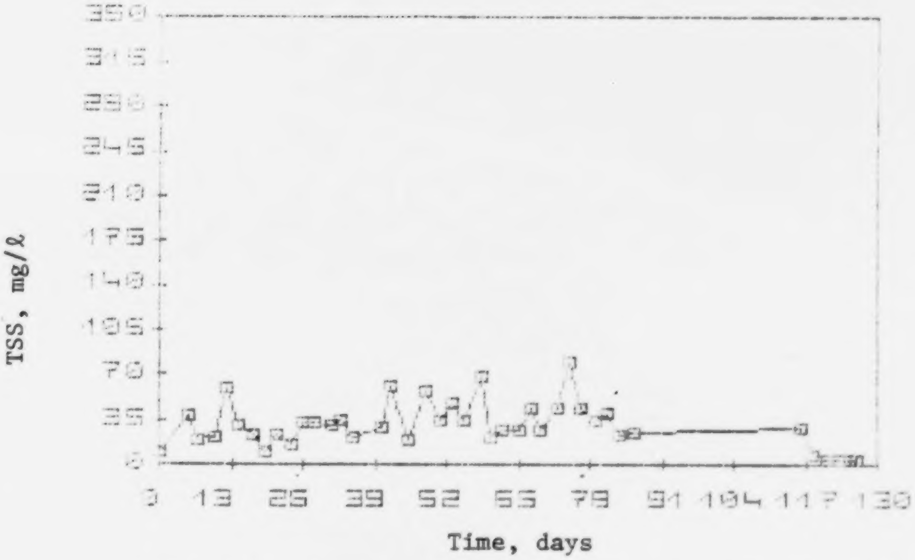


Figure B.45. Total suspended solids concentration of effluent sewage from the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

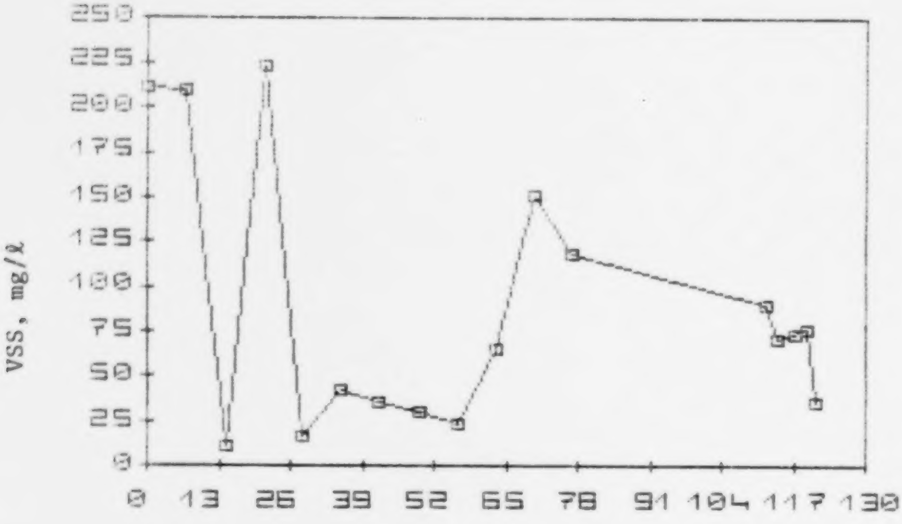


Figure B.46. Volatile suspended solids concentration of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 20, 1980.

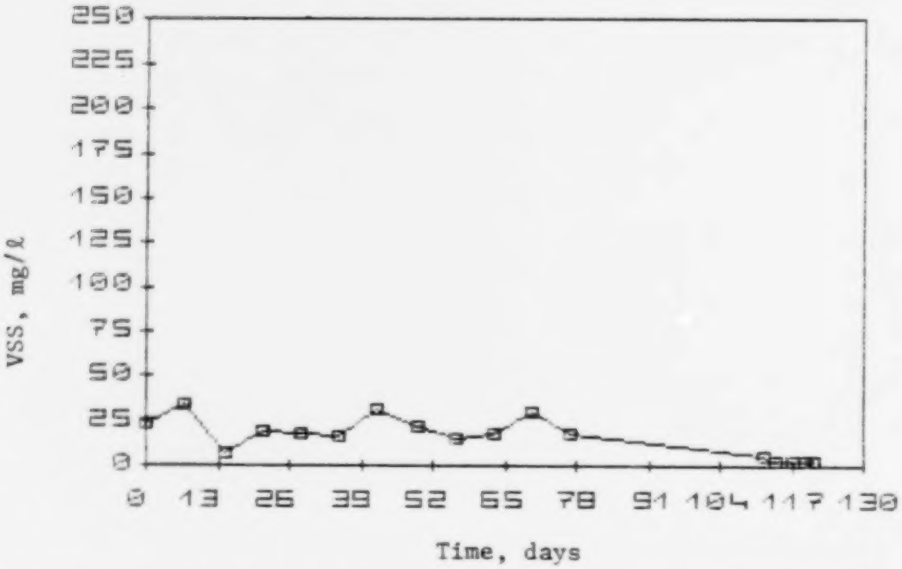


Figure B.47. Volatile suspended solids concentration of effluent sewage from the CRREL NFT unit. First day of analysis was February 20, 1980.

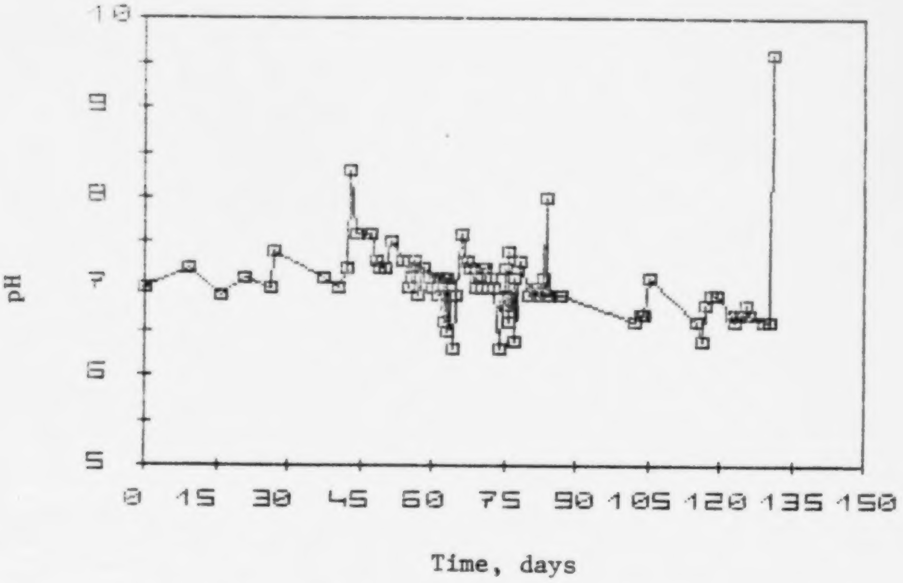


Figure B.48. pH of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

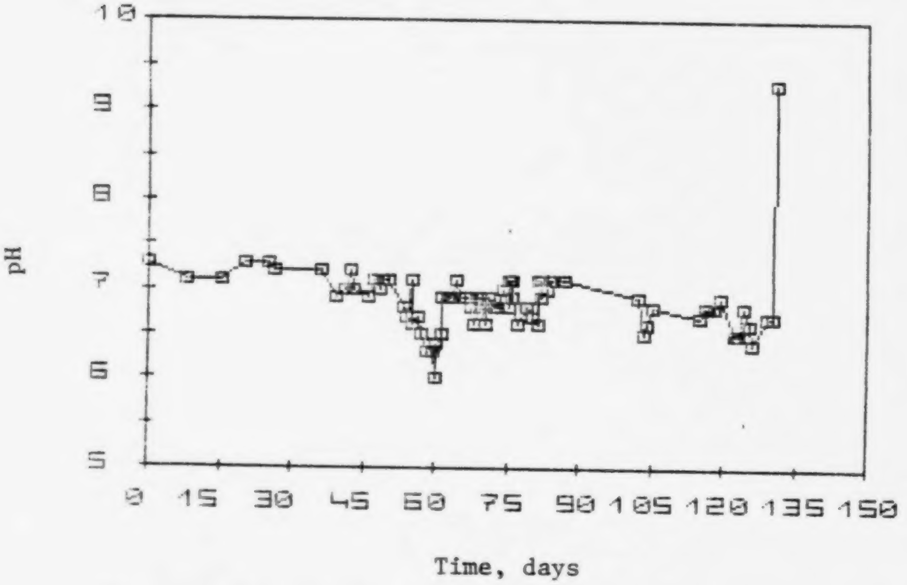


Figure B.49. pH of effluent sewage from the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

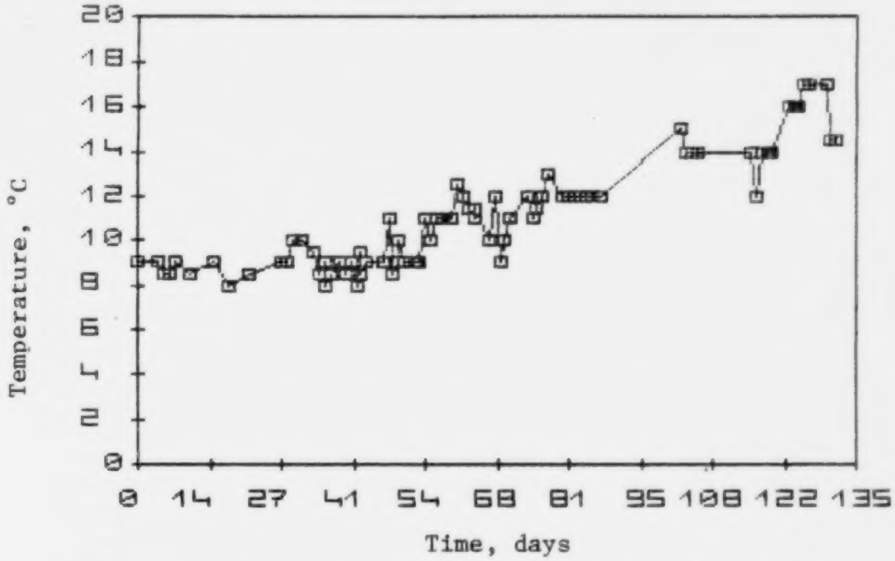


Figure B.50. Temperature of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

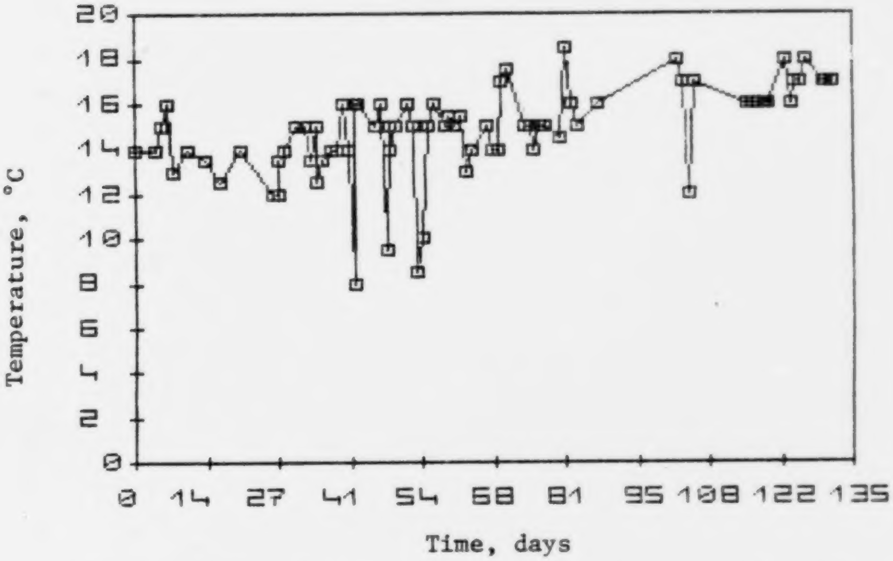


Figure B.51. Temperature of effluent sewage from the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

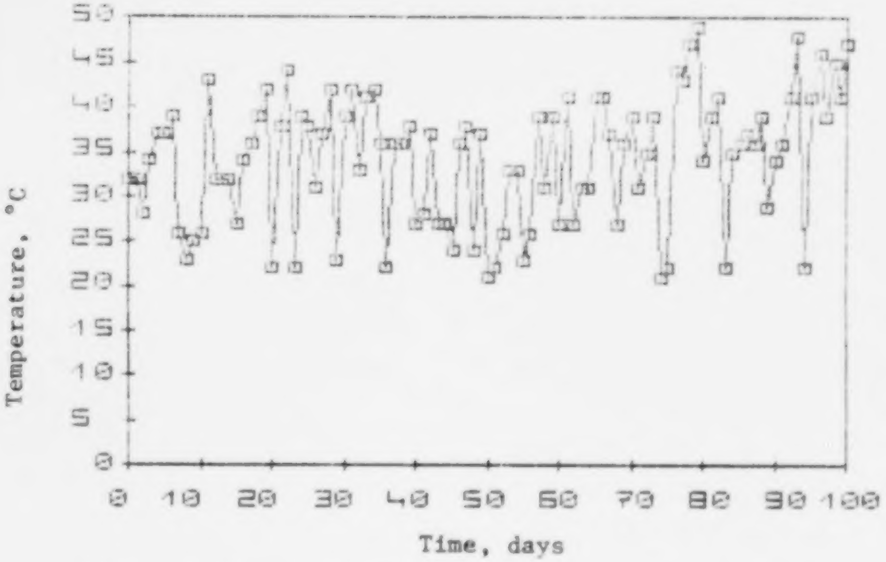


Figure B.52. Daily maximum air temperature in the CRREL greenhouse in Phase 1. First day of analysis was February 15, 1980.

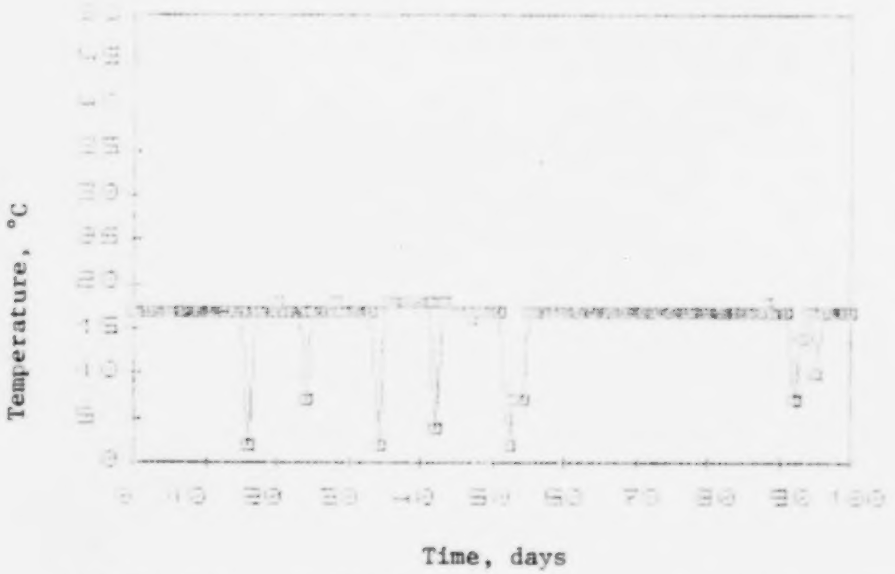


Figure B.53. Daily minimum air temperature in the CRREL greenhouse in Phase 1. First day of analysis was February 15, 1980.

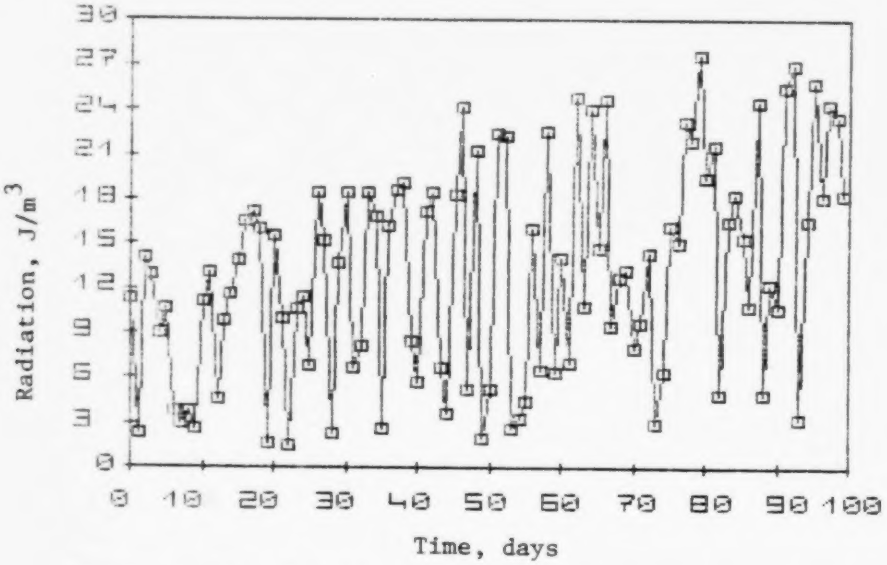


Figure B.54. Outside incident radiation at CRREL in Phase 1. First day of analysis was February 15, 1980.

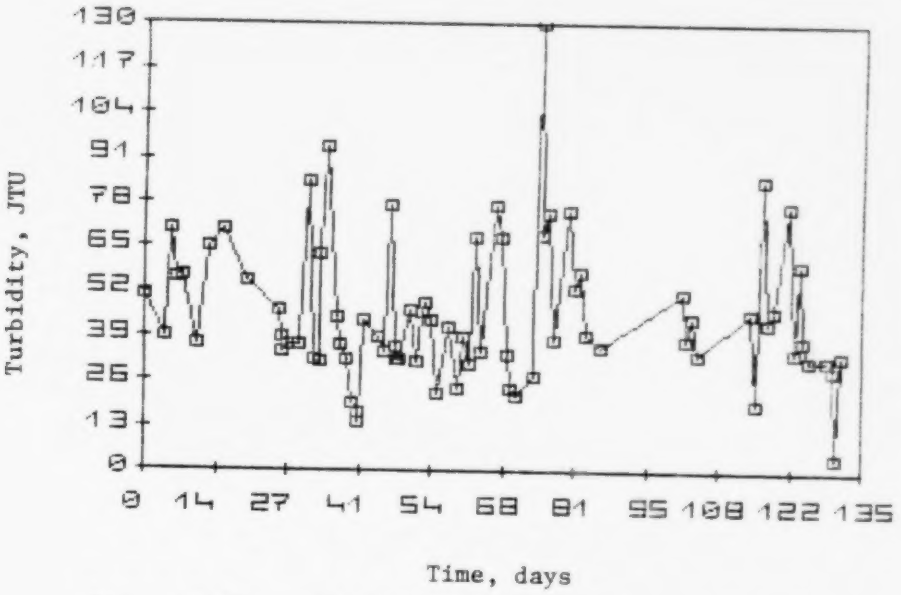


Figure B.55. Turbidity of influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

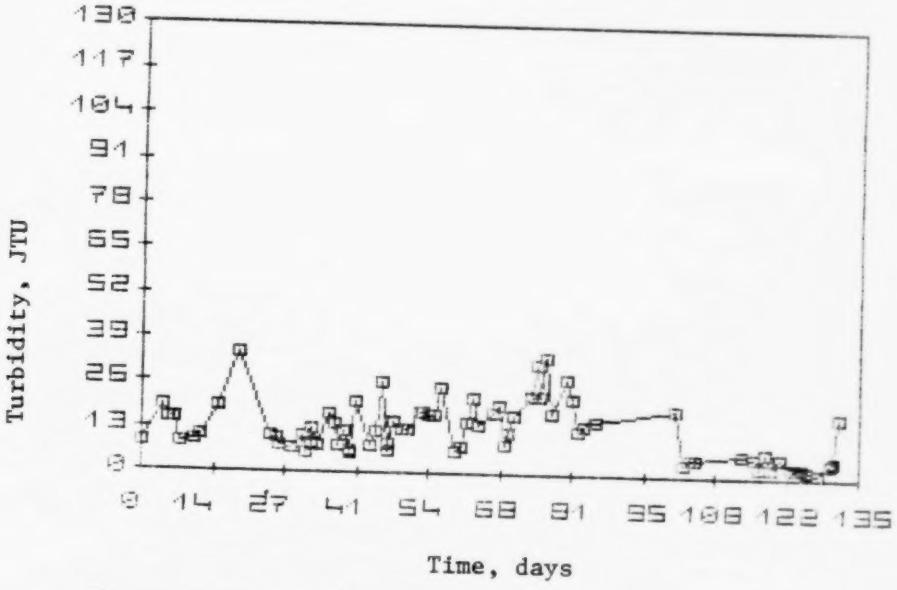


Figure B.56. Turbidity of effluent sewage from the CRREL NFT unit in Phase 1. First day of analysis was February 15, 1980.

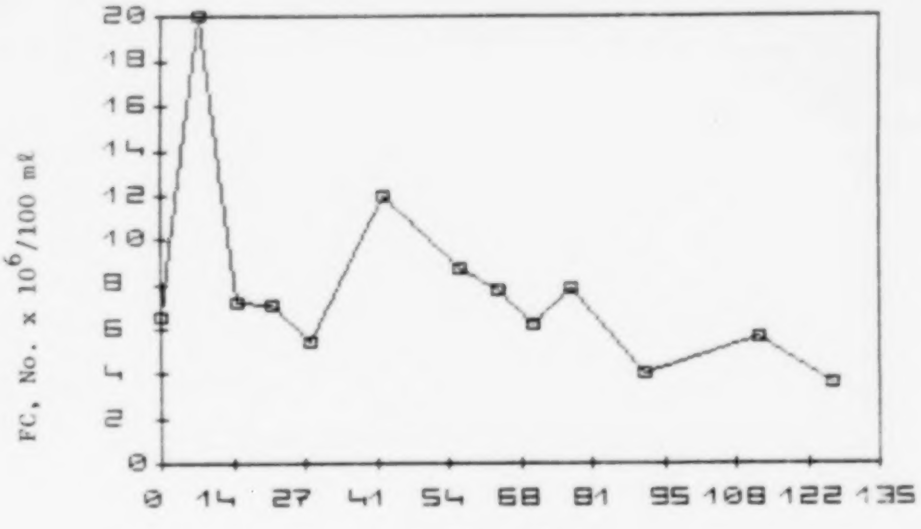


Figure B.57. Numbers of fecal coliforms in influent sewage to the CRREL NFT unit in Phase 1. First day of analysis was February 20, 1980.

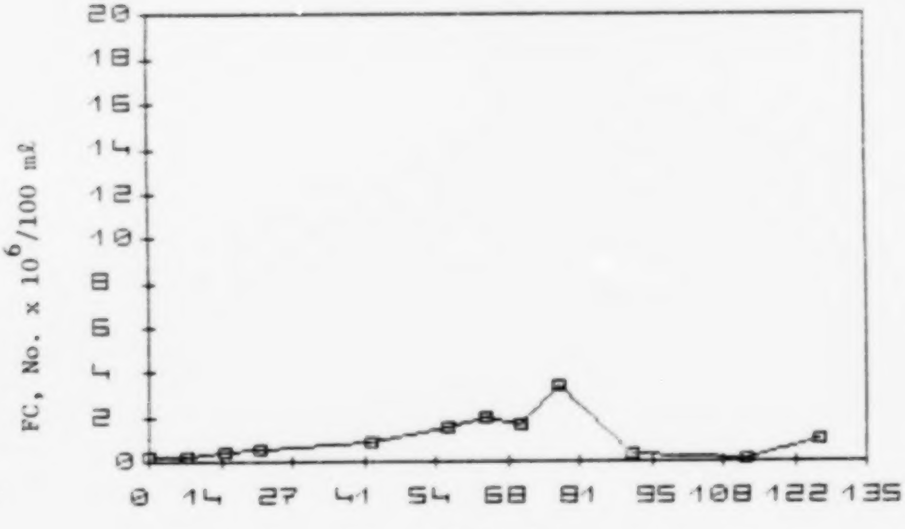


Figure B.58. Numbers of fecal coliforms in effluent sewage from the CRREL NFT unit in Phase 1. First day of analysis was February 20, 1980.

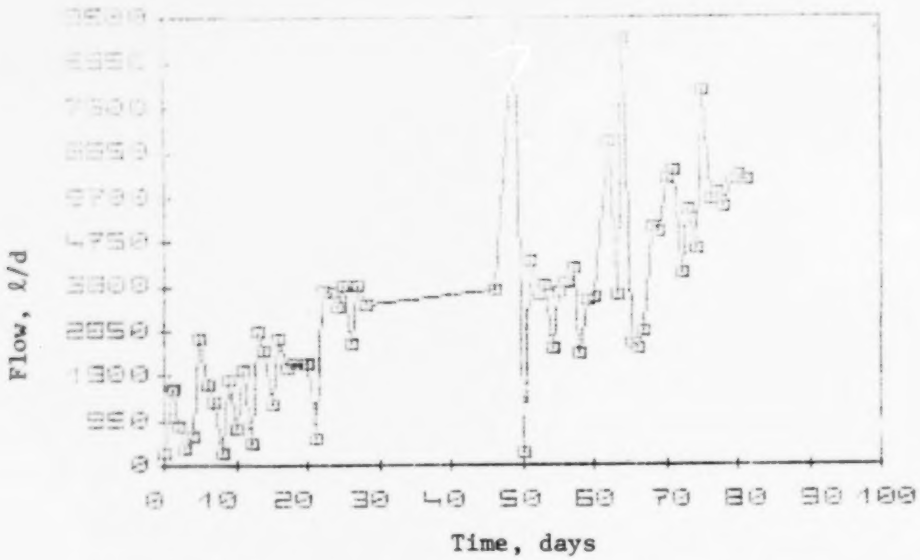


Figure B.59. Daily influent sewage flow to the Hanover NFT unit, beginning March 2, 1981.

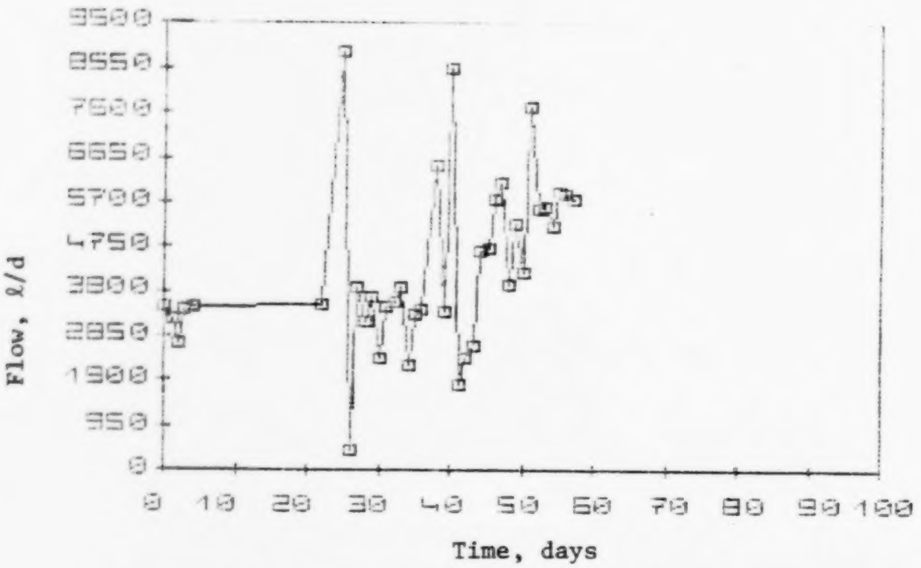


Figure B.60. Daily effluent sewage flow from the Hanover NFT unit, beginning March 26, 1981.

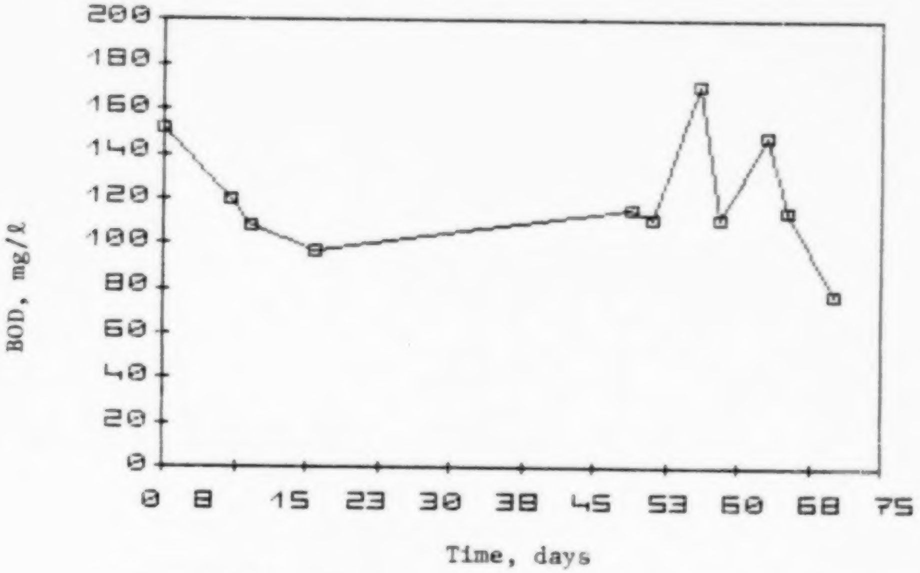


Figure B.61. Biological oxygen demand concentration of influent sewage to the first unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

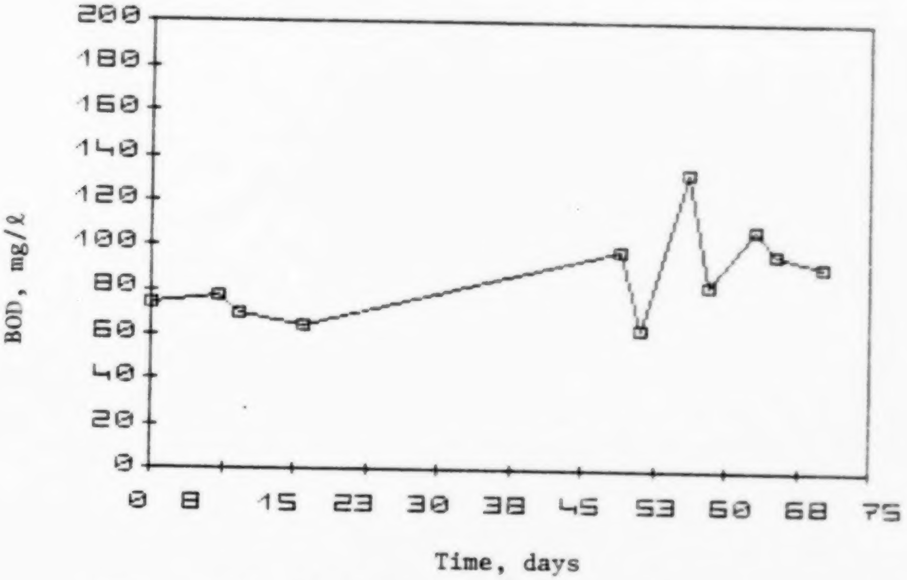
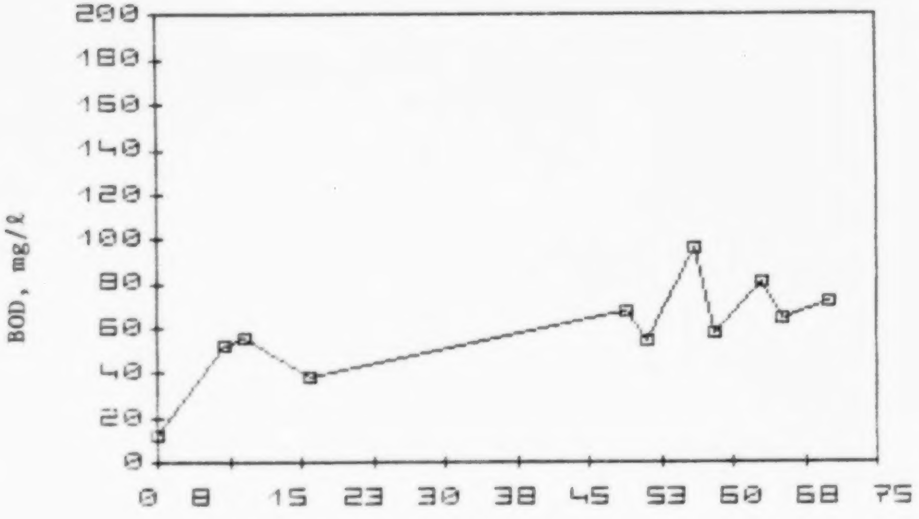
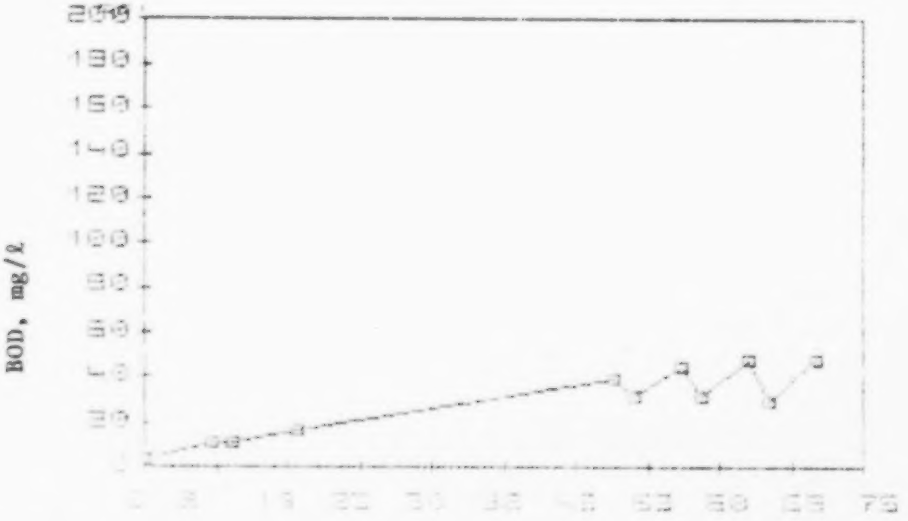


Figure B.62. Biological oxygen demand concentration of effluent sewage from the first unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981. These values also represent influent concentrations to the second unit.



Time, days

Figure B.63. Biological oxygen demand concentrations of effluent sewage from the second unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981. These values also represent influent concentrations to the third unit.



Time, days

Figure B.64. Biological oxygen demand concentrations of effluent sewage from the third unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

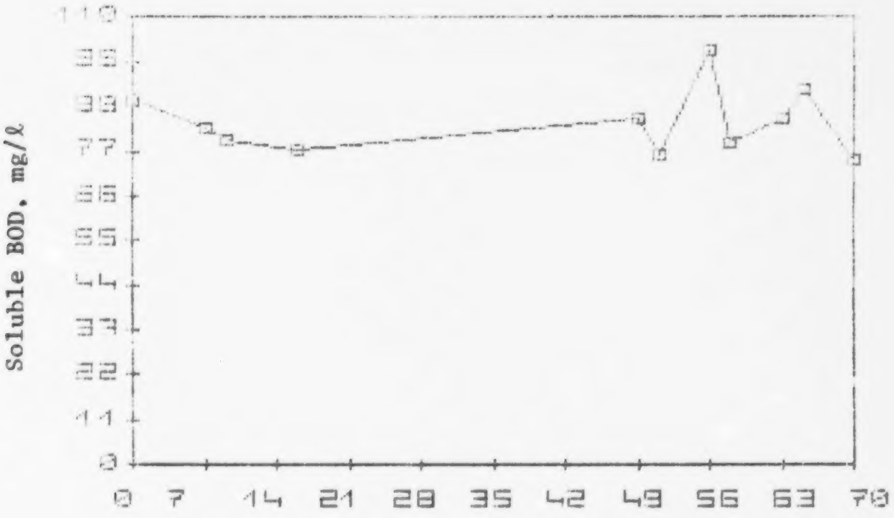


Figure B.65. Soluble biological oxygen demand concentration of influent sewage to the first unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

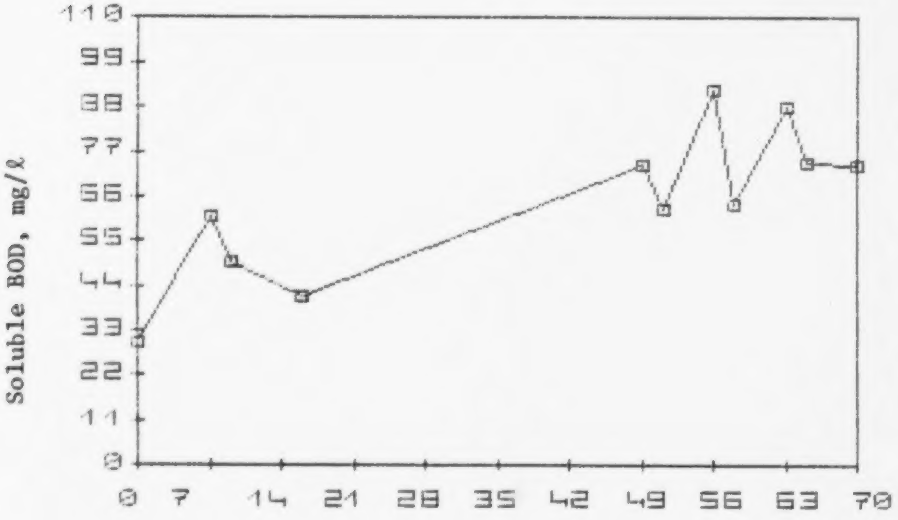


Figure B.66. Soluble biological oxygen demand concentration of effluent sewage from the first unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

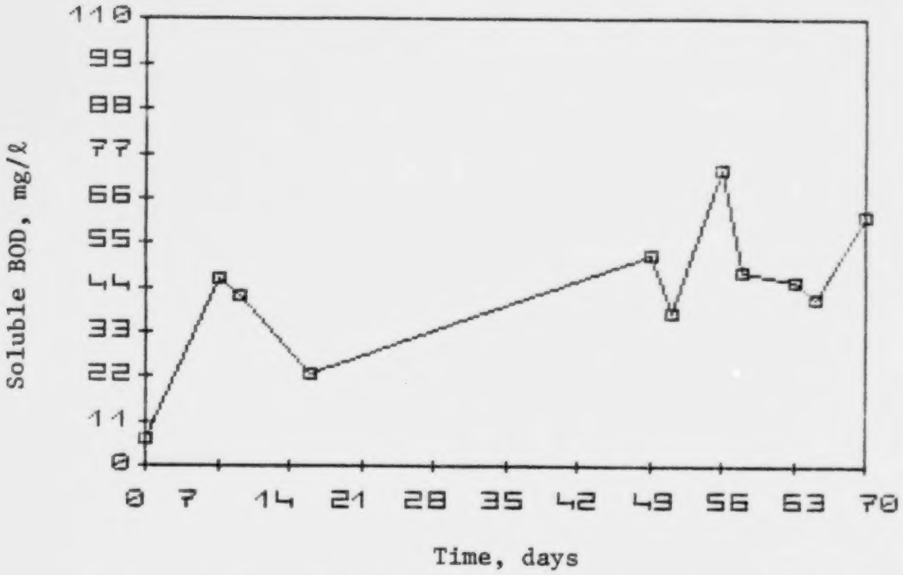


Figure B.67. Soluble biological oxygen demand concentration of effluent sewage from the second unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

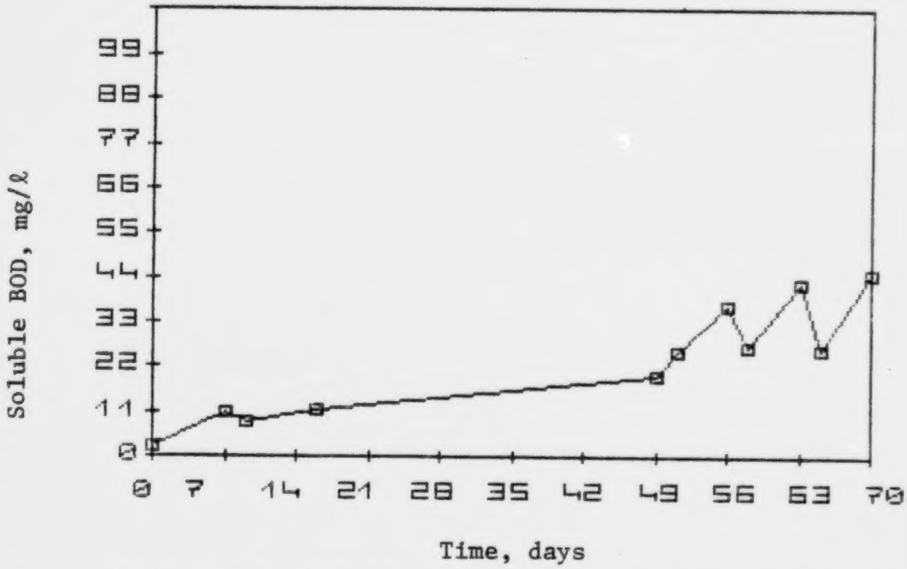


Figure B.68. Soluble biological oxygen demand concentration of effluent sewage from the third unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

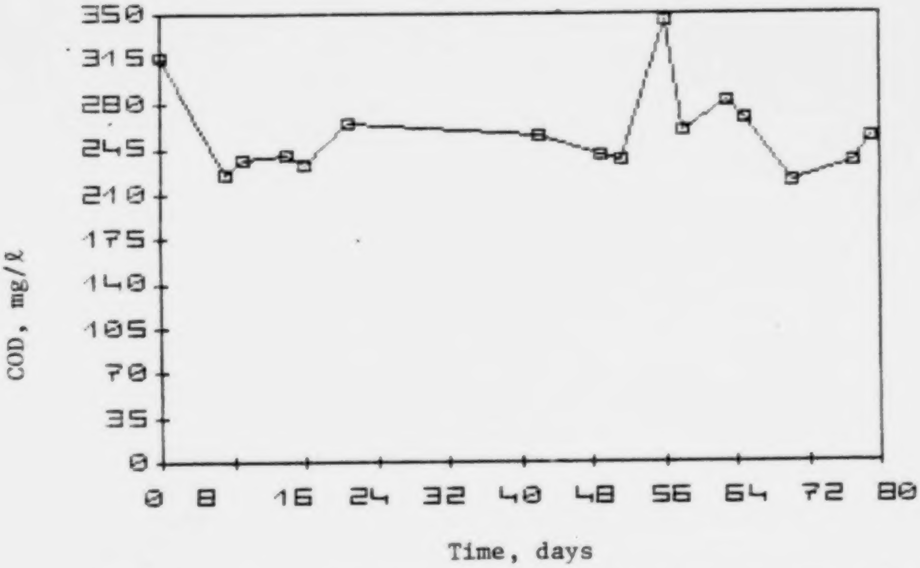


Figure B.69. Chemical oxygen demand concentration of influent sewage to the first unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

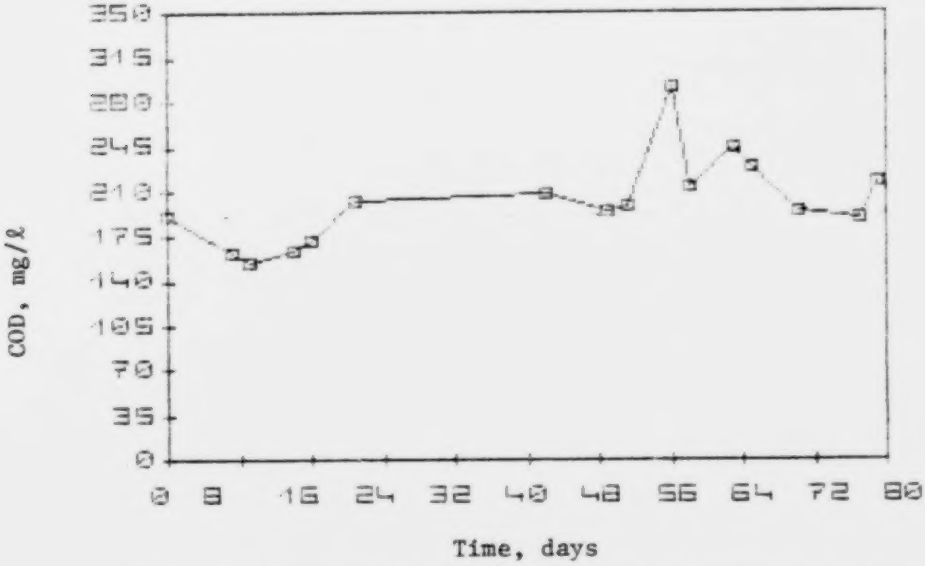


Figure B.70. Chemical oxygen demand concentration of effluent sewage from the first unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

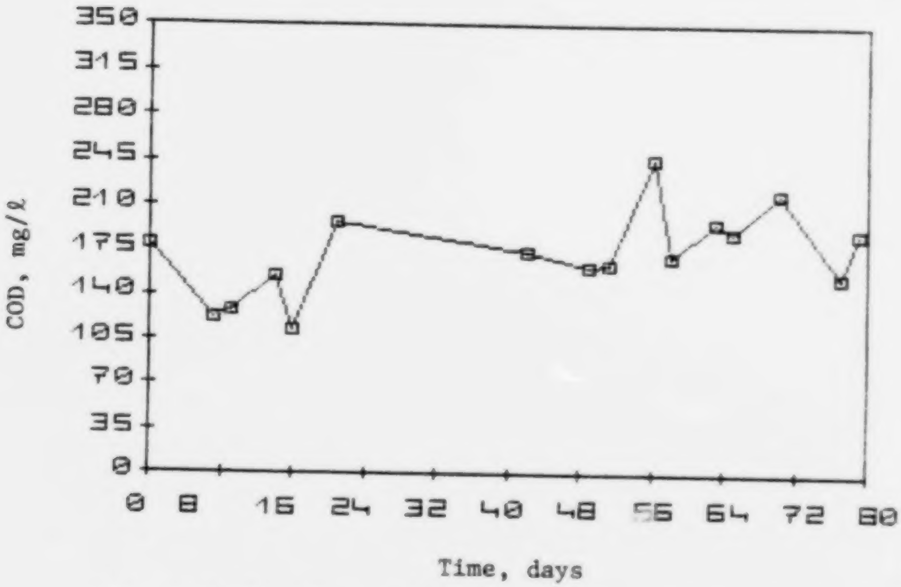


Figure B.71. Chemical oxygen demand concentration of effluent sewage from the second unit in the Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

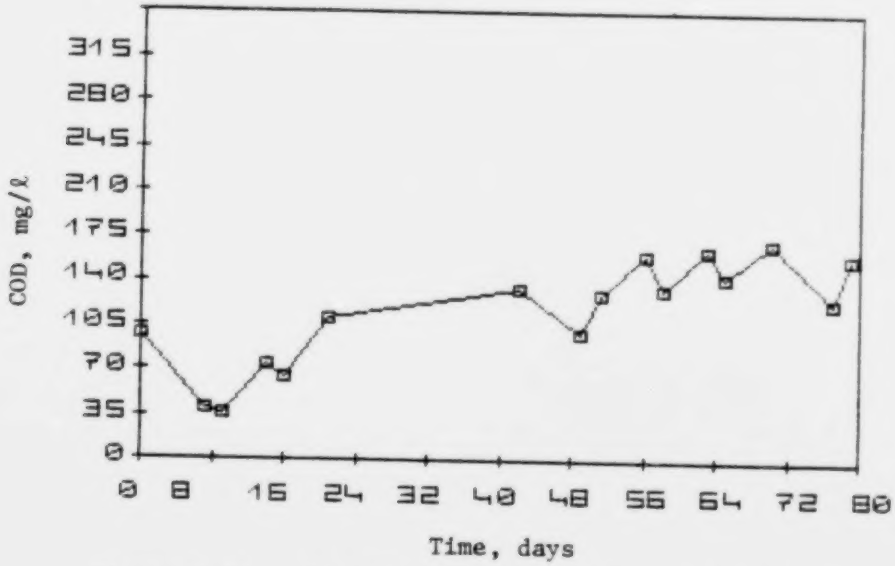


Figure B.72. Chemical oxygen demand concentration of effluent sewage from the third unit of the Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

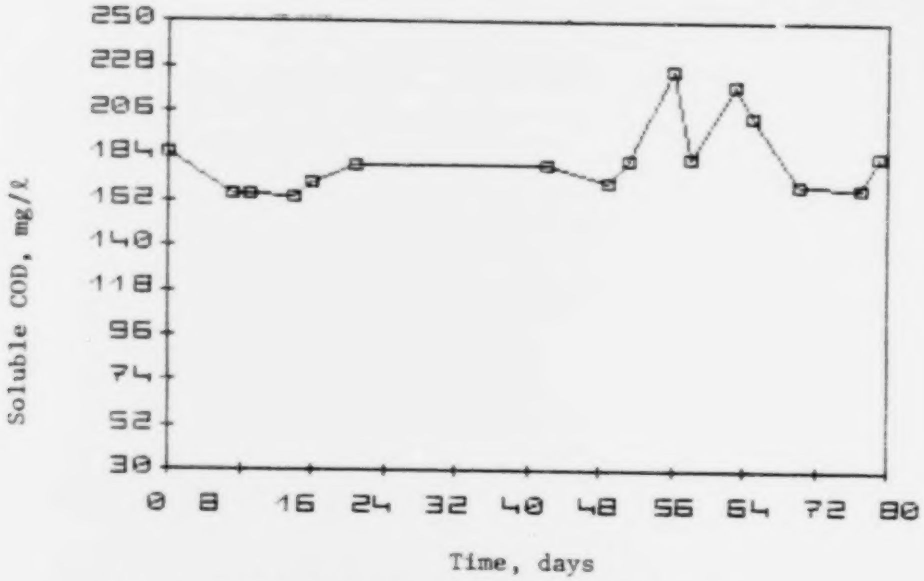


Figure B.73. Soluble chemical oxygen demand concentration of influent sewage to first unit of Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

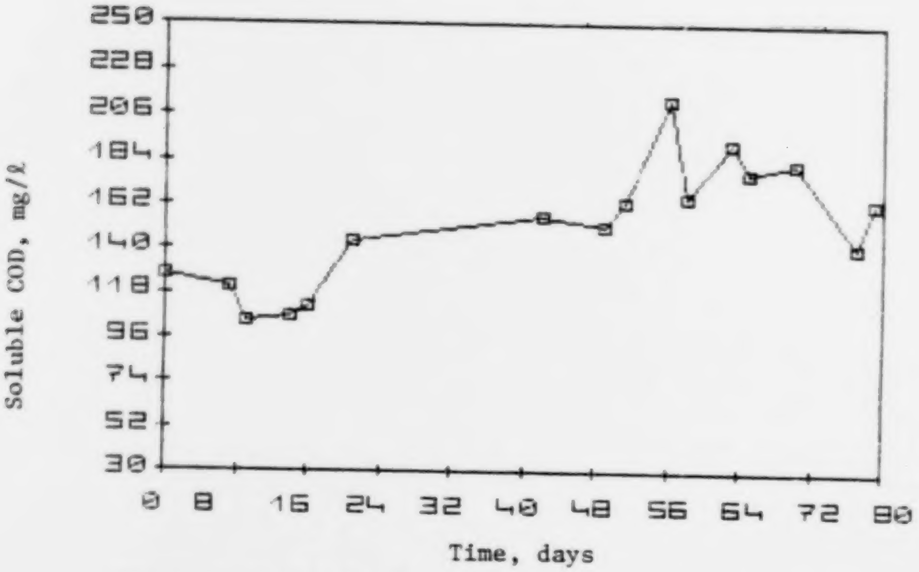


Figure B.74. Soluble chemical oxygen demand concentration of effluent sewage from first unit of Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

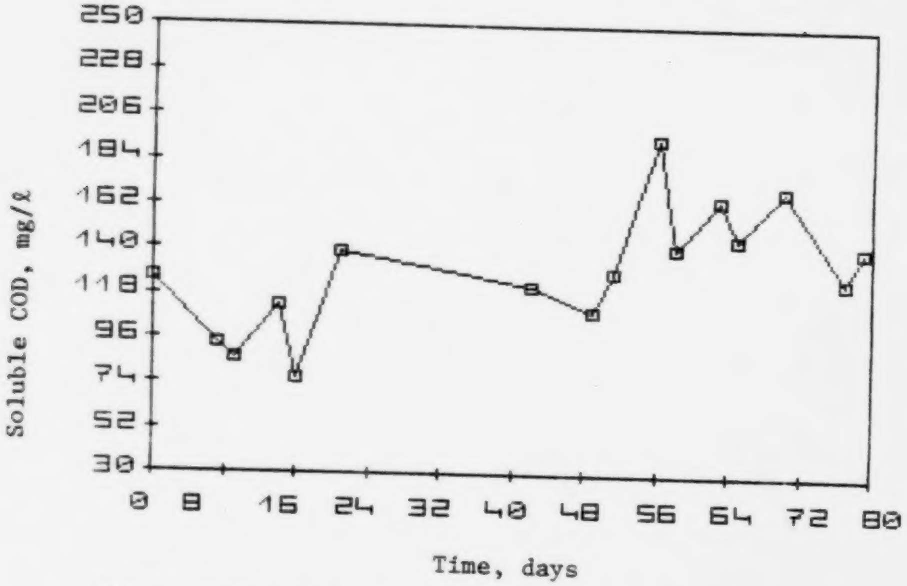


Figure B.75. Soluble chemical oxygen demand concentration of effluent sewage from second unit of Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

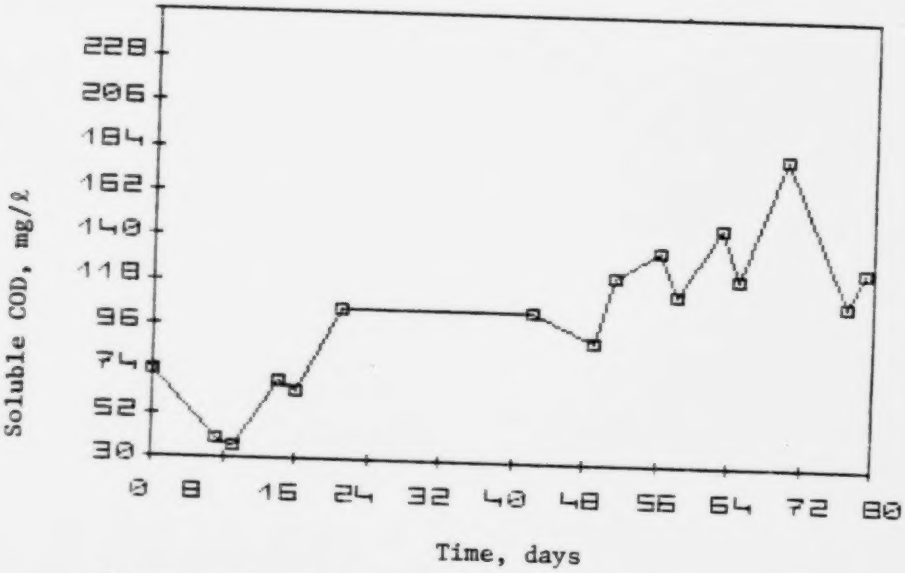


Figure B.76. Soluble chemical oxygen demand concentration of effluent sewage from third unit of Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

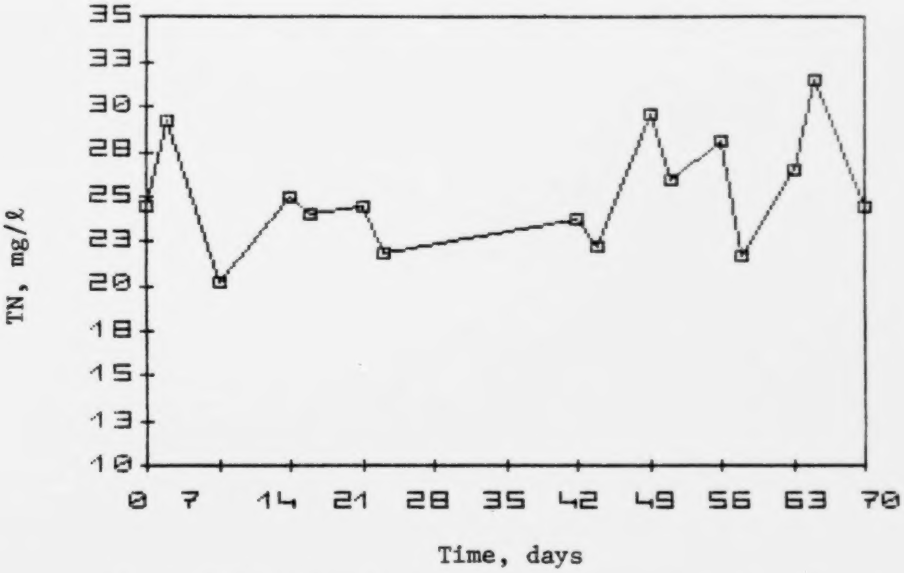


Figure B.77. Total nitrogen concentration of influent sewage to the first unit of Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

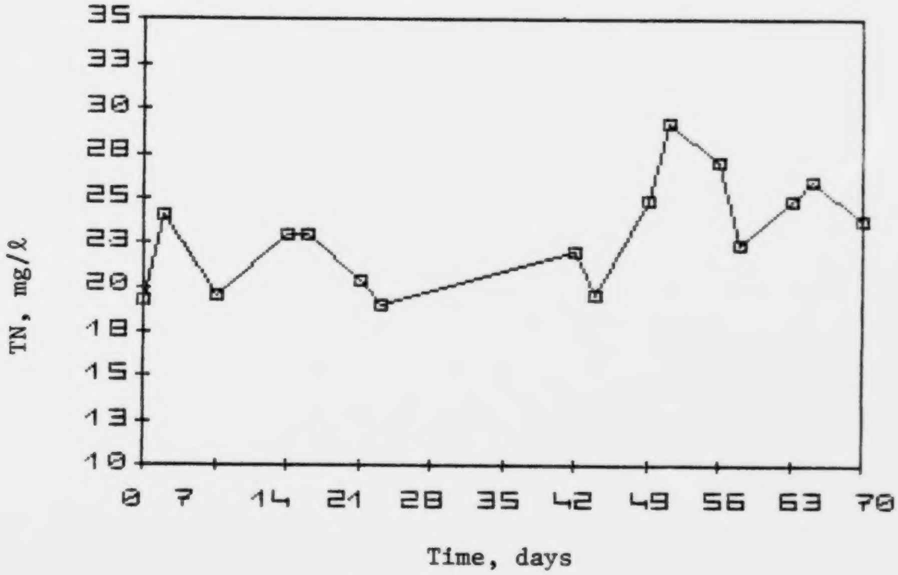


Figure B.78. Total nitrogen concentration in effluent sewage from the first unit of Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

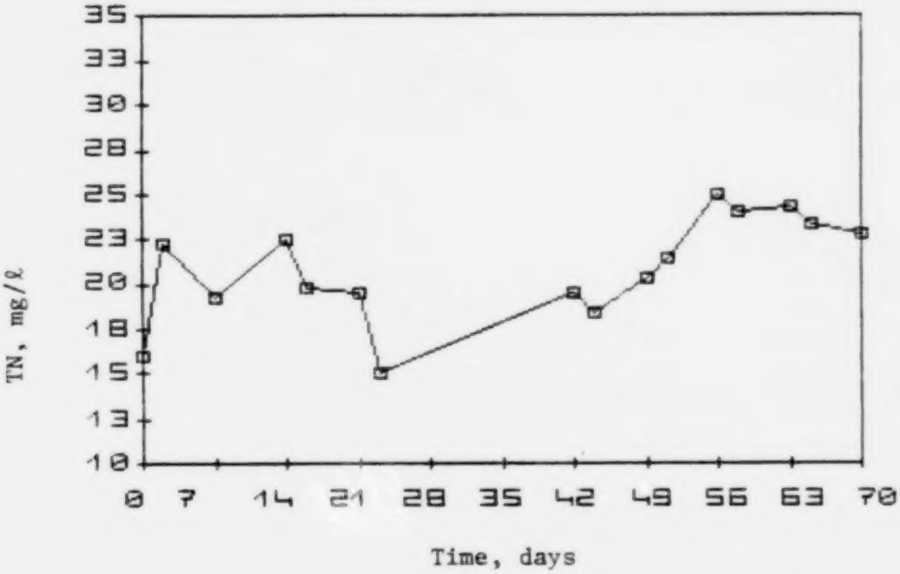


Figure B.79. Total nitrogen concentration of effluent sewage from second unit of Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

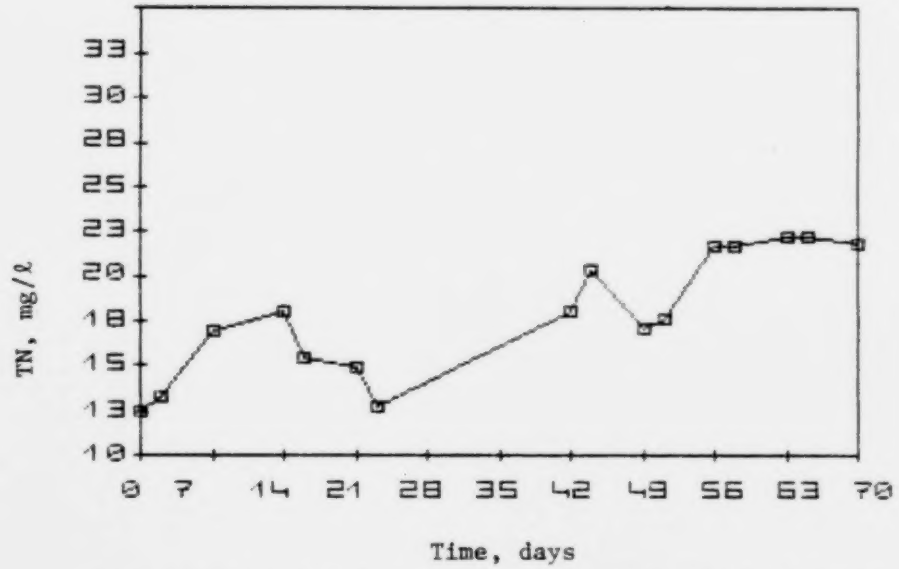
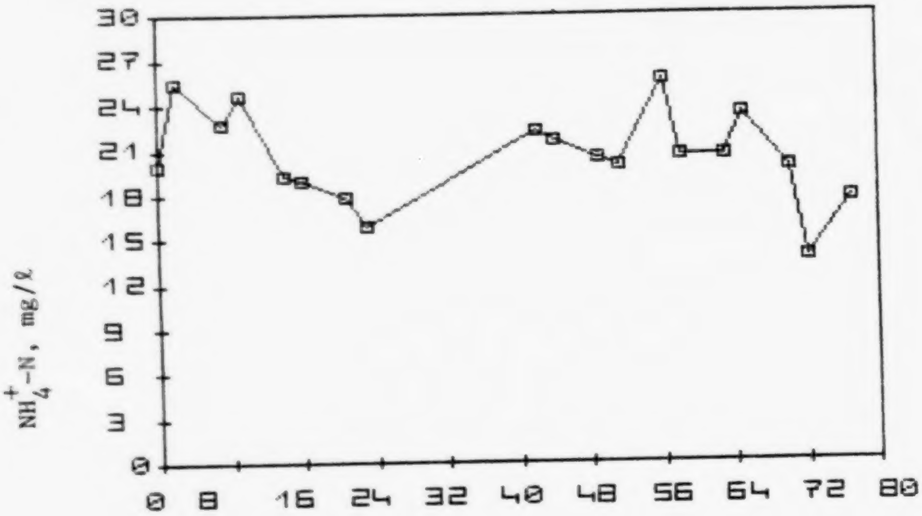
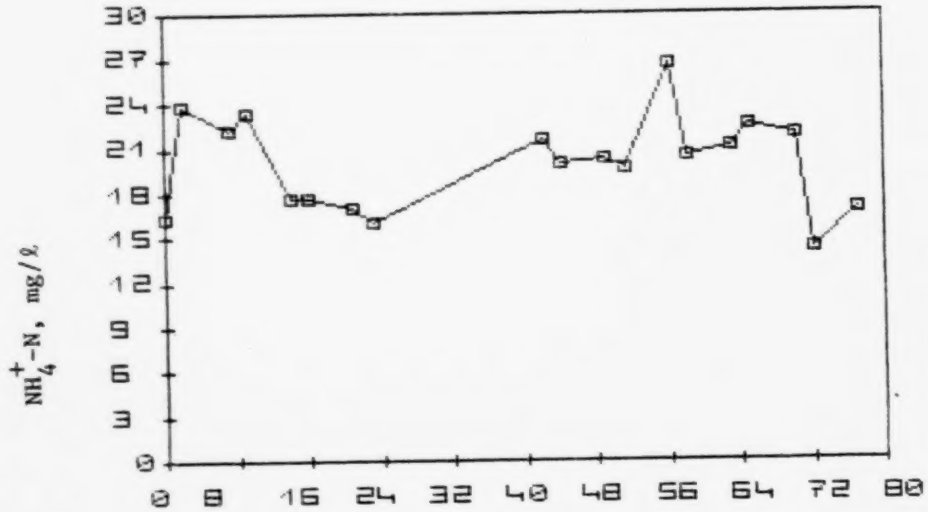


Figure B.80. Total nitrogen concentration of effluent sewage from third unit of Hanover NFT in Phase 1. First day of analysis was March 4, 1981.



Time, days

Figure B.81. Ammonium concentration of influent sewage to first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.



Time, days

Figure B.82. Ammonium concentration of effluent sewage from first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

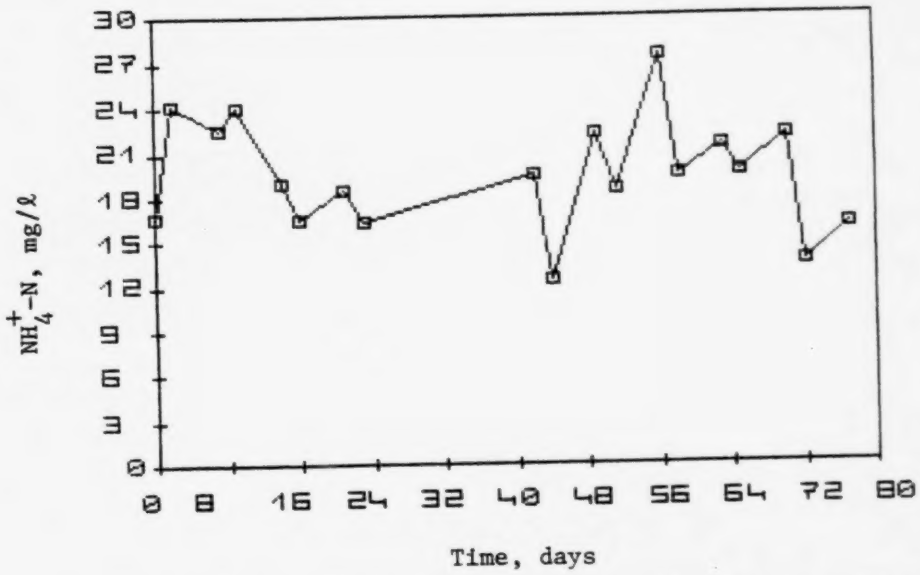


Figure B.83. Ammonium concentration of effluent sewage from second unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

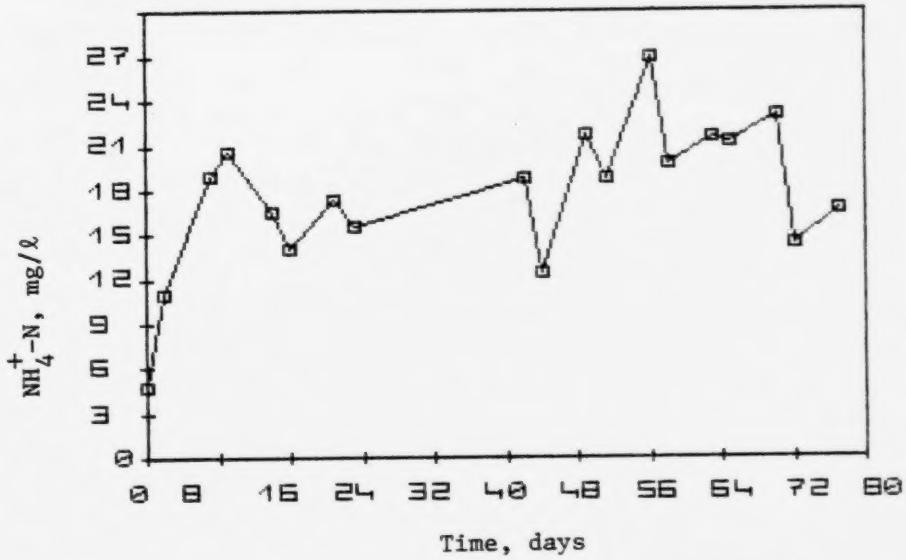


Figure B.84. Ammonium concentration of effluent sewage from third unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

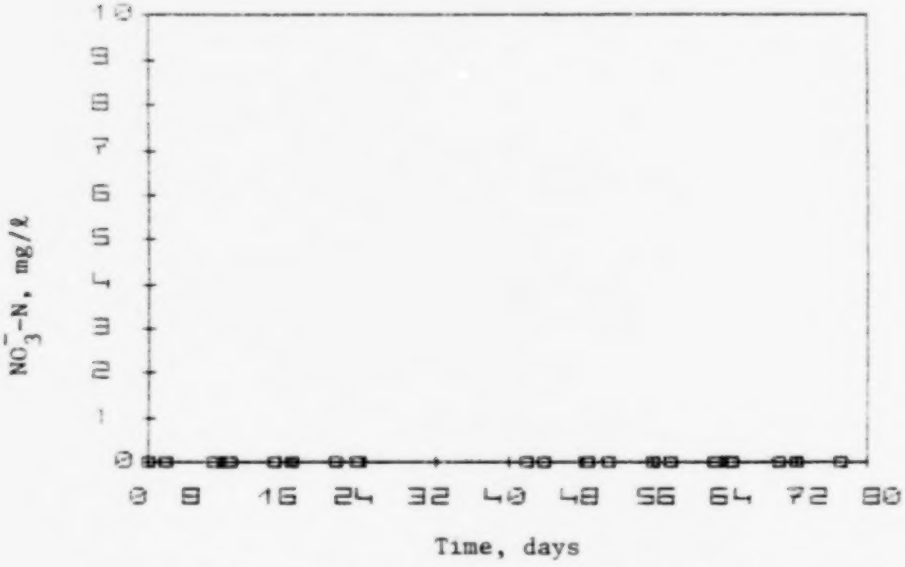


Figure B.85. Nitrate concentration of influent sewage to first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

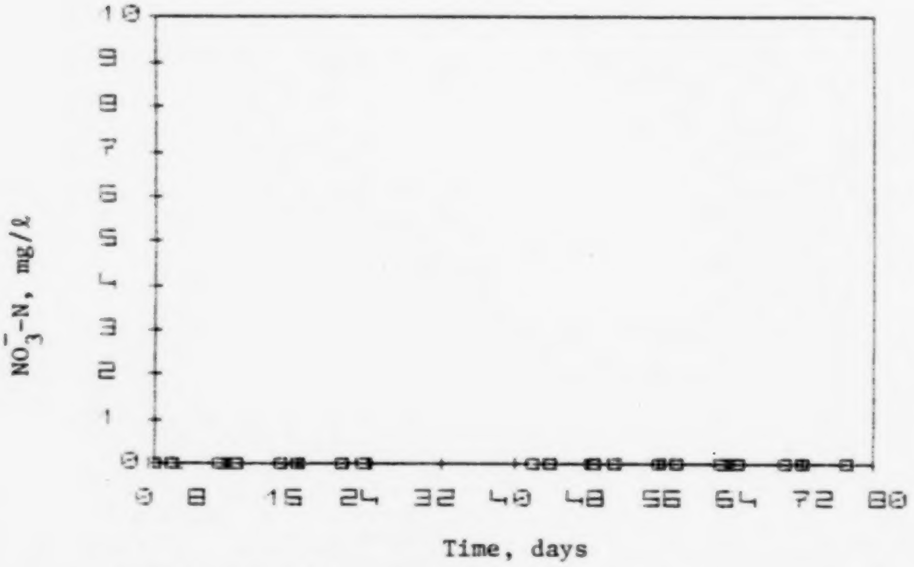


Figure B.86. Nitrate concentration of effluent sewage from first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

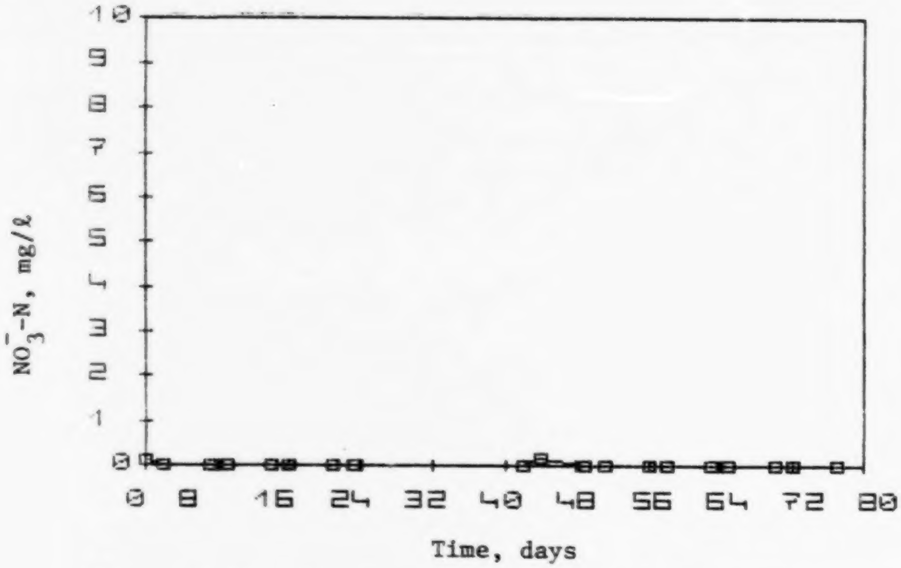
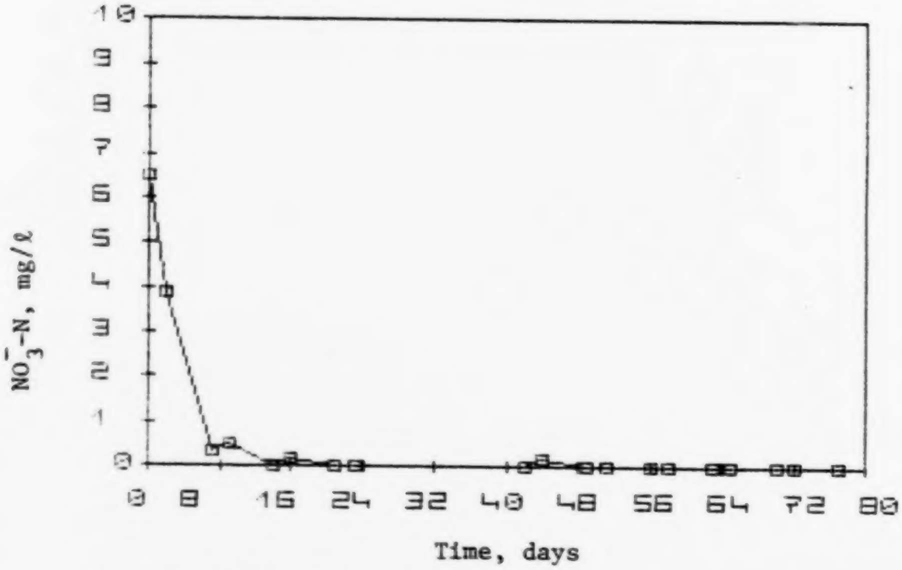


Figure B.87. Nitrate concentration of effluent sewage from second unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.



Fiyure B.88. Nitrate concentration of effluent sewage from third unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

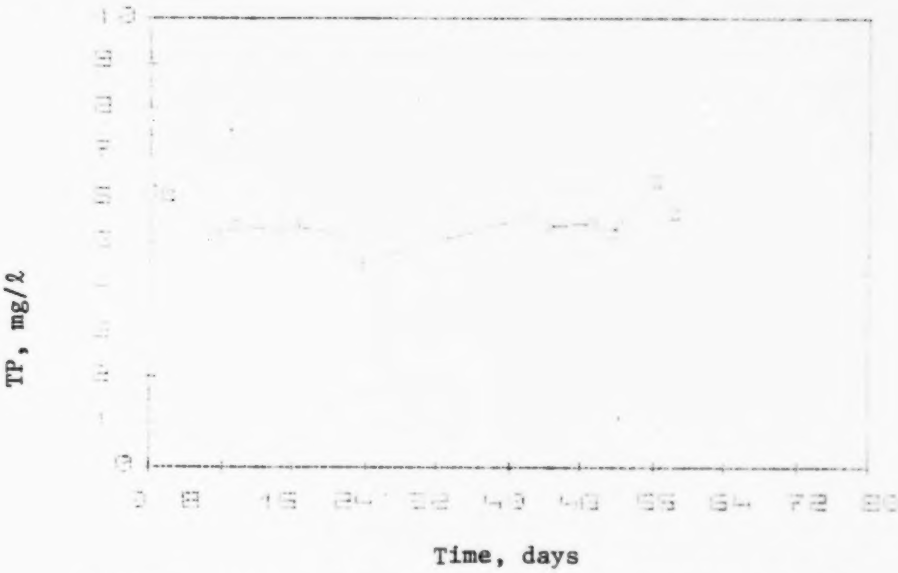


Figure B.89. Total phosphorus concentration of influent sewage to first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

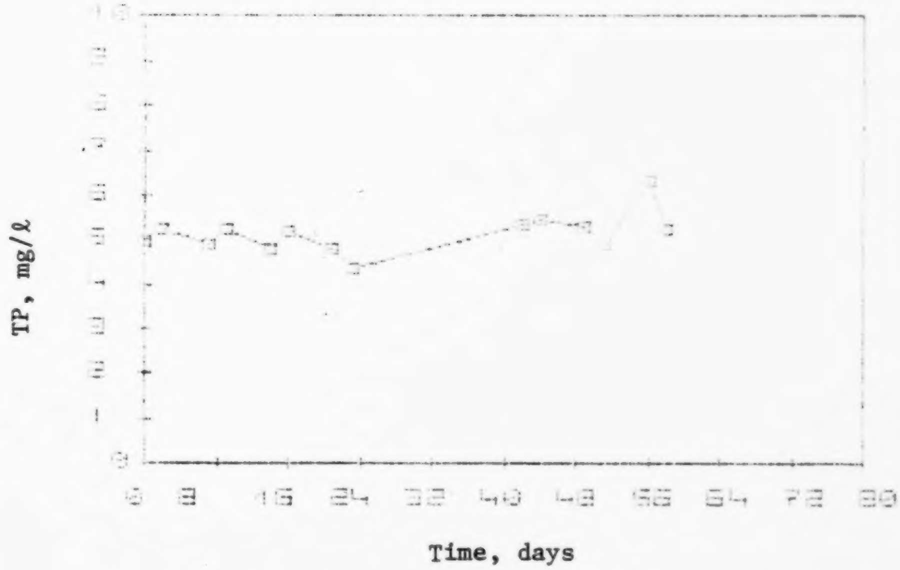


Figure B.90. Total phosphorus concentration of effluent sewage from first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

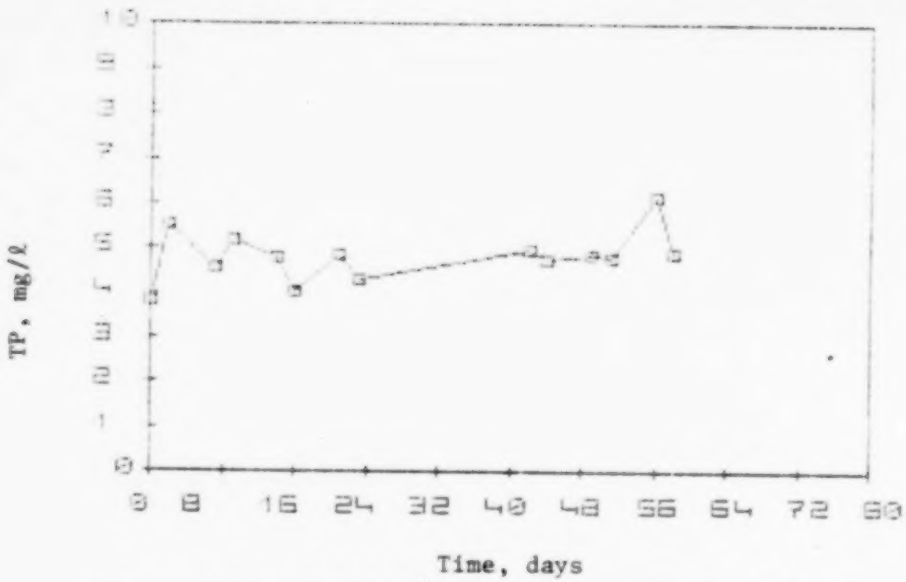


Figure B.91. Total phosphorus concentration of effluent sewage from second unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

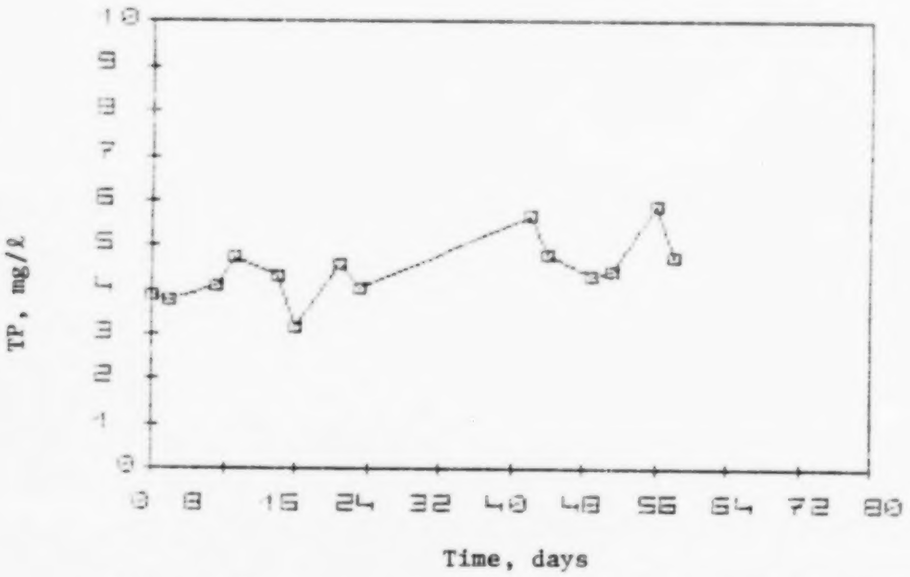


Figure B.92. Total phosphorus concentration of effluent sewage from third unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

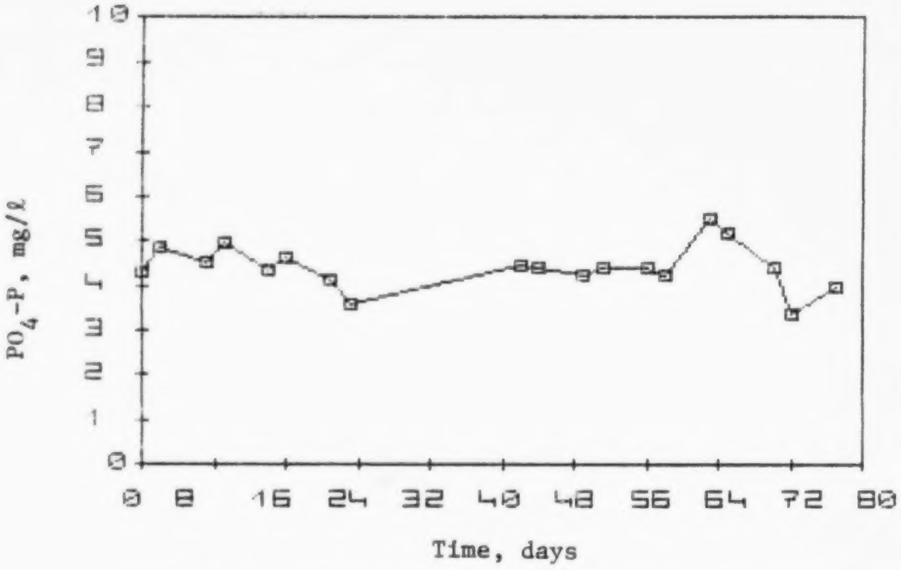


Figure B.93. Orthophosphate concentration of influent sewage to first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

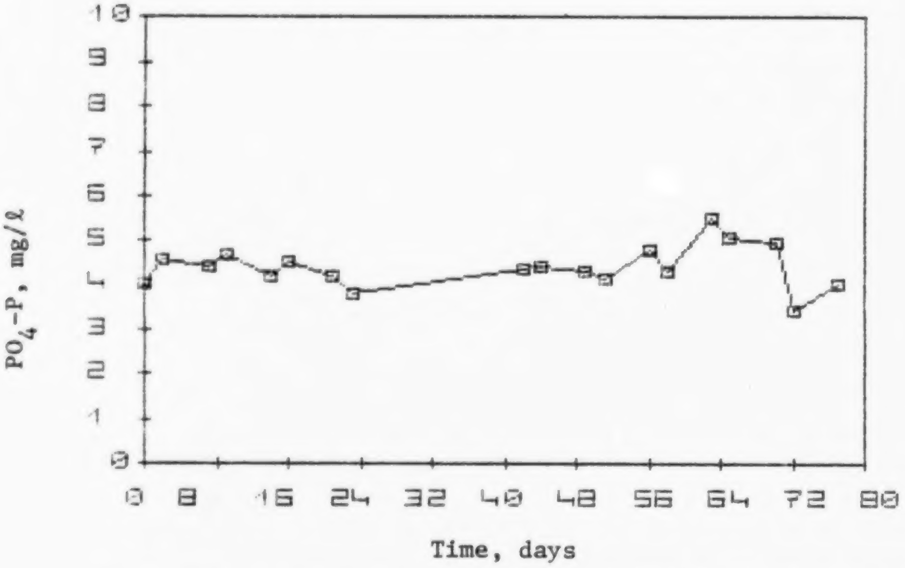
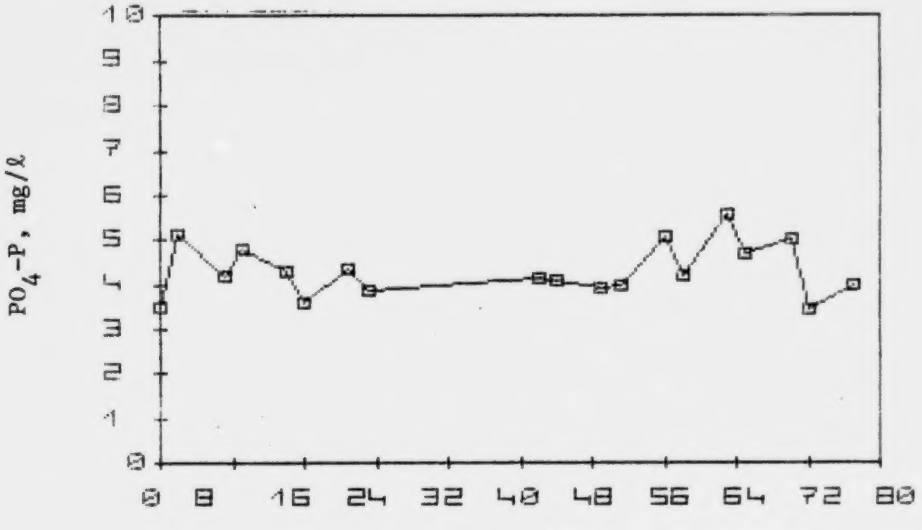
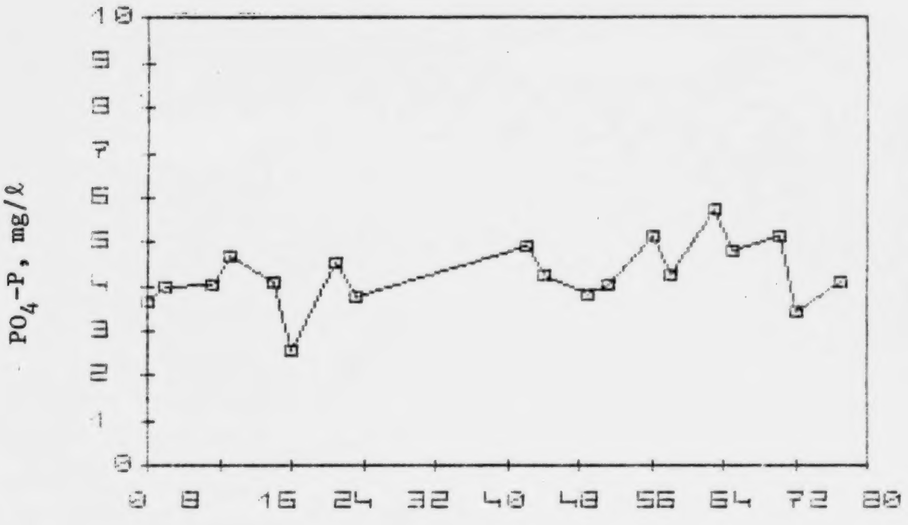


Figure B.94. Orthophosphate concentration of effluent sewage from first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.



Time, days

Figure B.95. Orthophosphate concentration of effluent sewage from second unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.



Time, days

Figure B.96. Orthophosphate concentration of effluent sewage from third unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

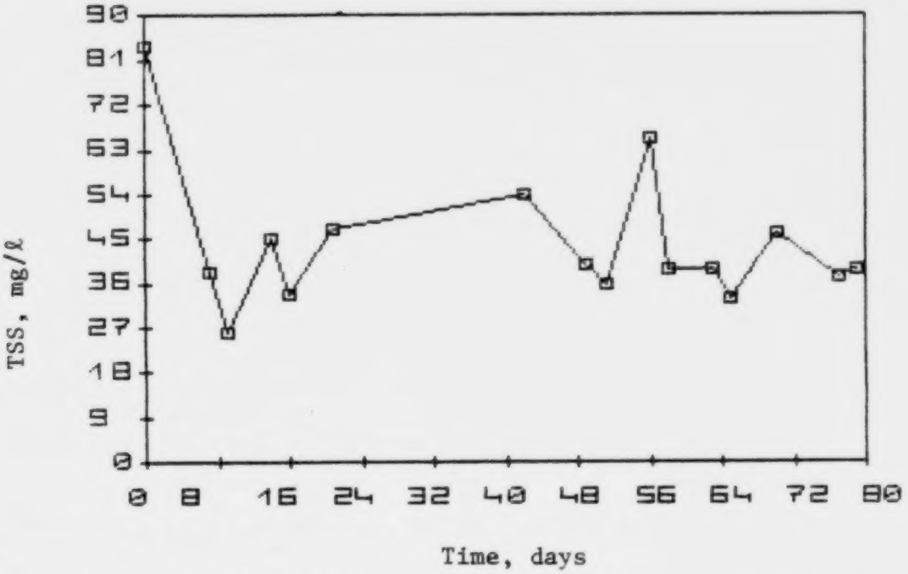


Figure B.97. Total suspended solids concentration of influent sewage to first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

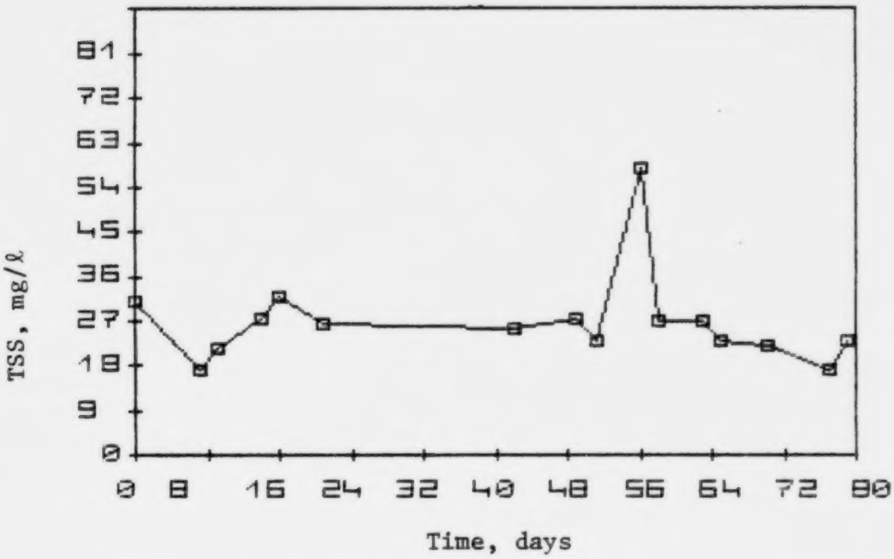


Figure B.98. Total suspended solids concentration of effluent sewage from first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

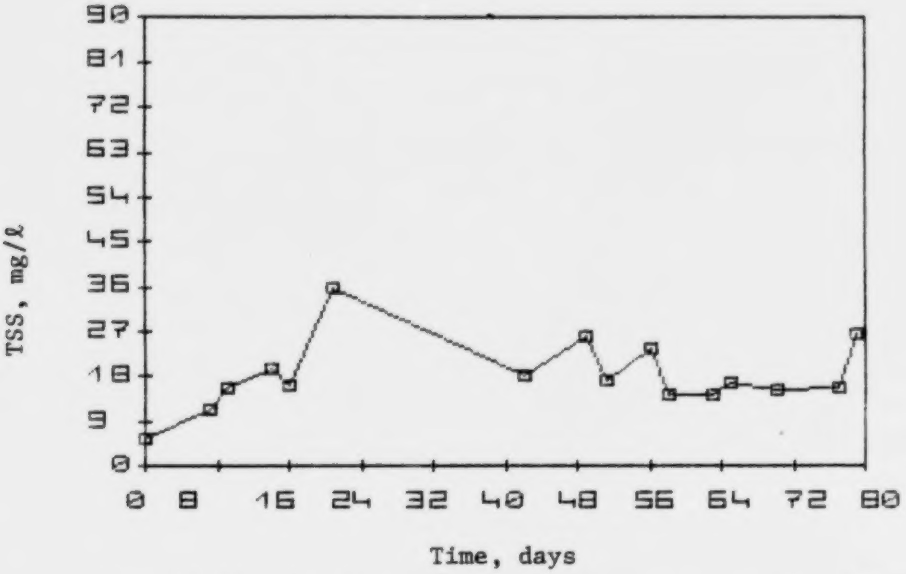


Figure B.99. Total suspended solids concentration of effluent sewage from second unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

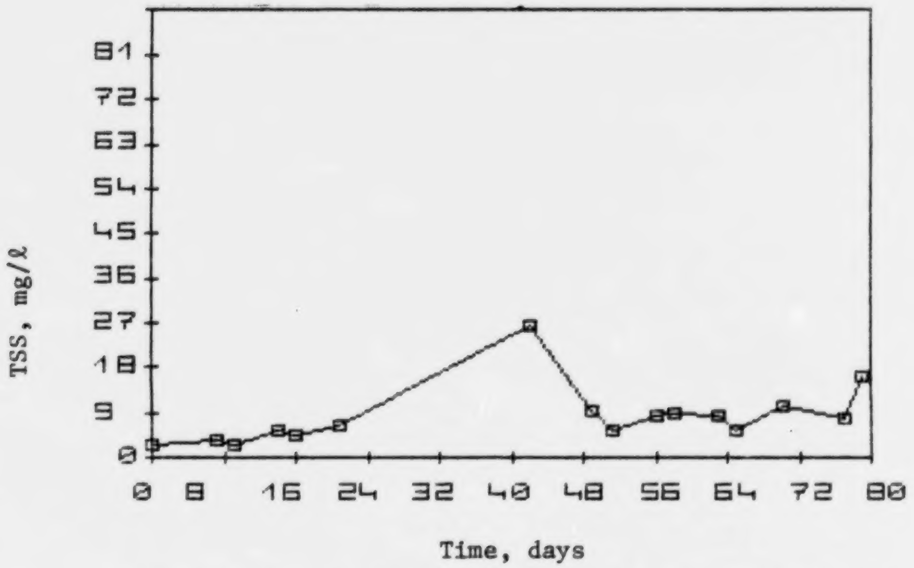


Figure B.100. Total suspended solids concentration of effluent sewage from third unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

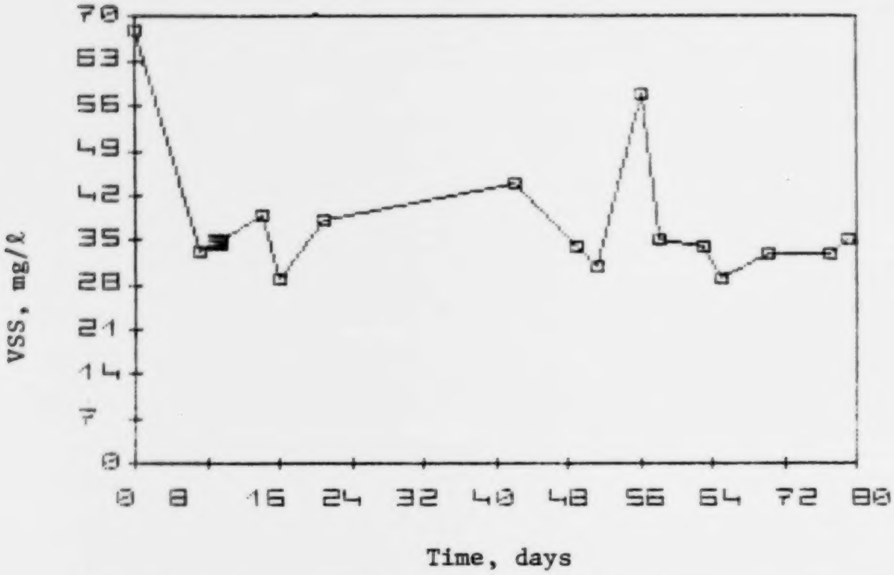


Figure B.101. Volatile suspended solids concentration of influent sewage to the first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

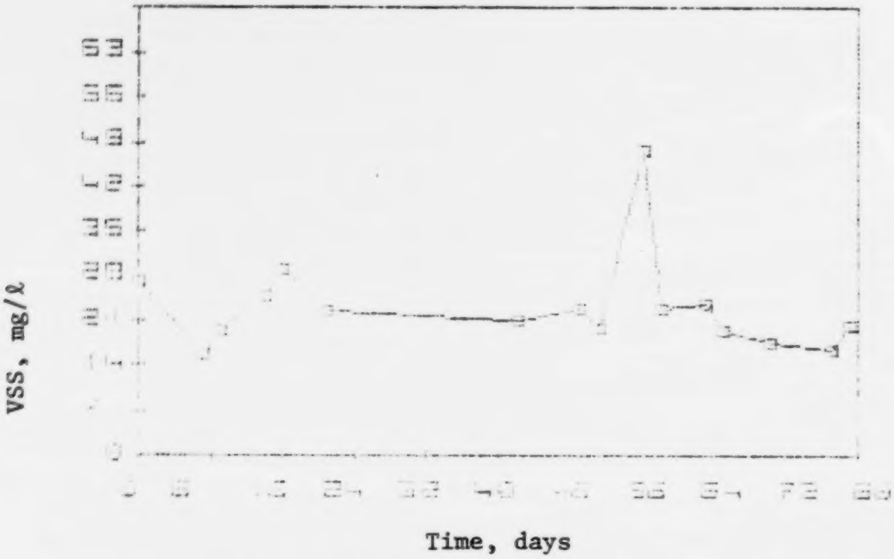


Figure B.102. Volatile suspended solids concentration of effluent sewage from first unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

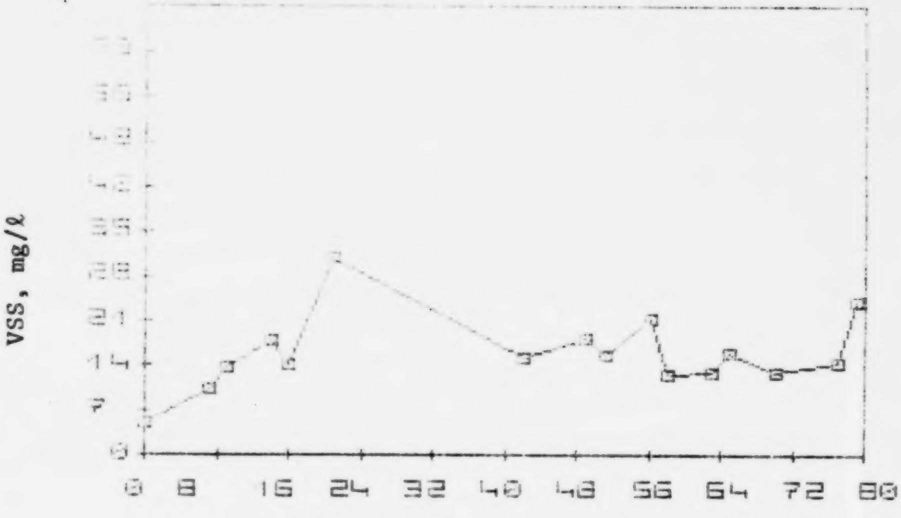


Figure B.103. Volatile suspended solids concentration of effluent sewage from second unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

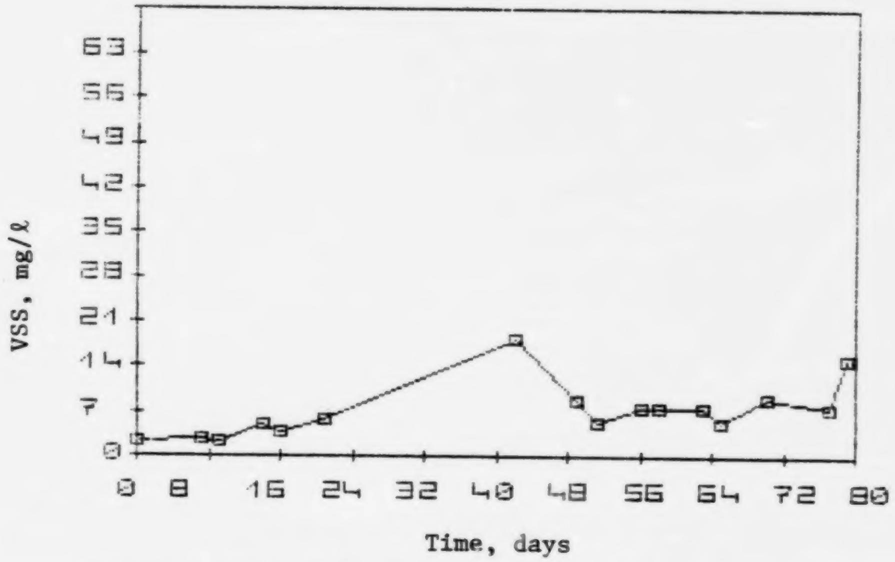


Figure B.104. Volatile suspended solids concentration of effluent sewage from third unit in Hanover NFT in Phase 1. First day of analysis was March 4, 1981.

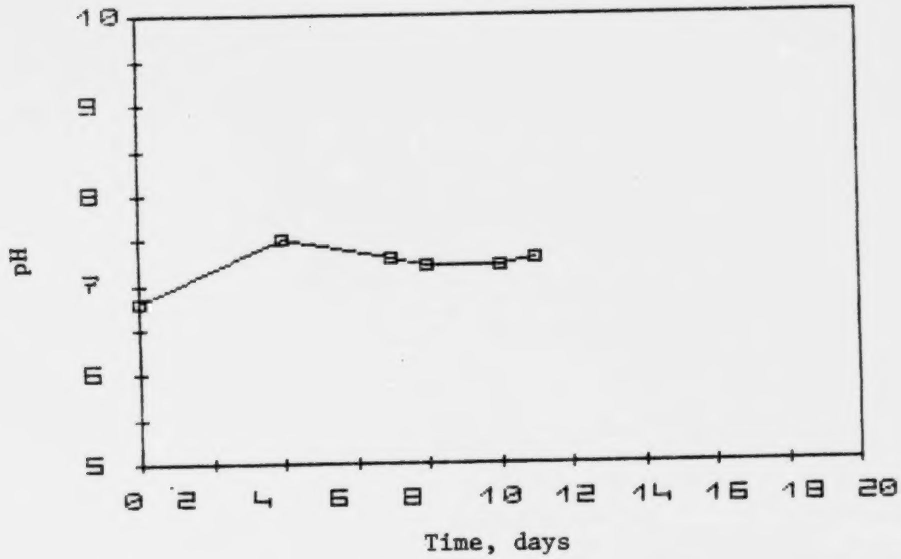


Figure B.105. pH of influent sewage to first unit in Hanover NFT in Phase 1. First day of analysis was March 2, 1981.

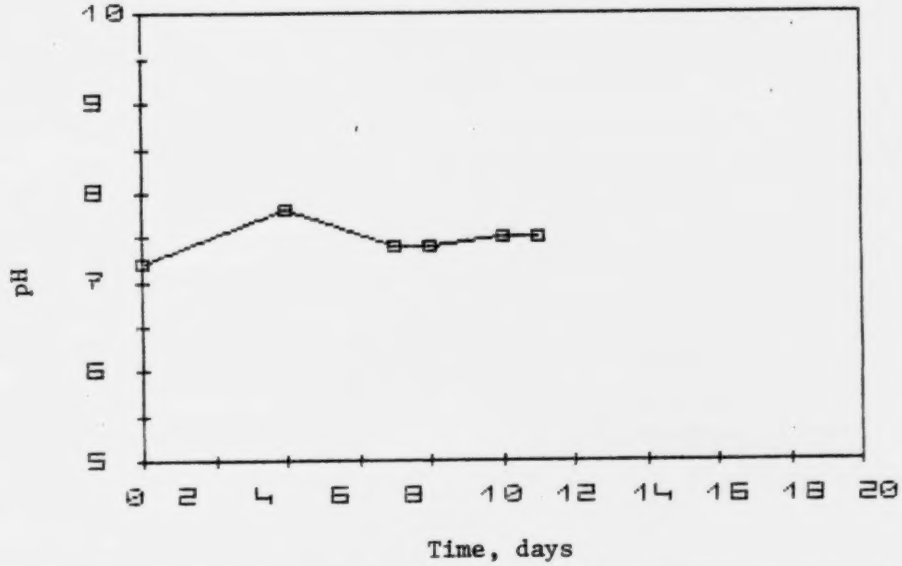


Figure B.106. pH of effluent sewage from first unit in Hanover NFT in Phase 1. First day of analysis was March 2, 1981.

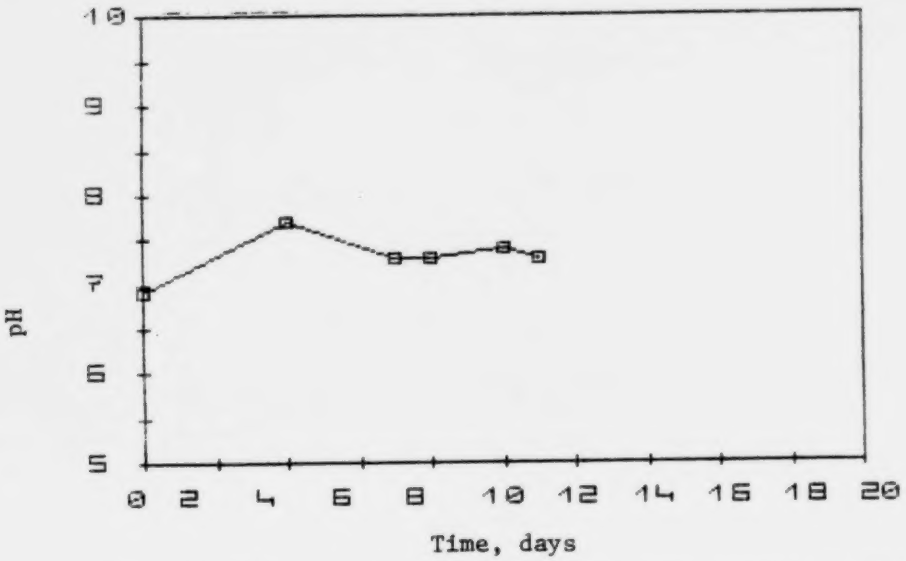


Figure B.107. pH of effluent sewage from second unit in Hanover NFT in Phase 1. First day of analysis was March 2, 1981.

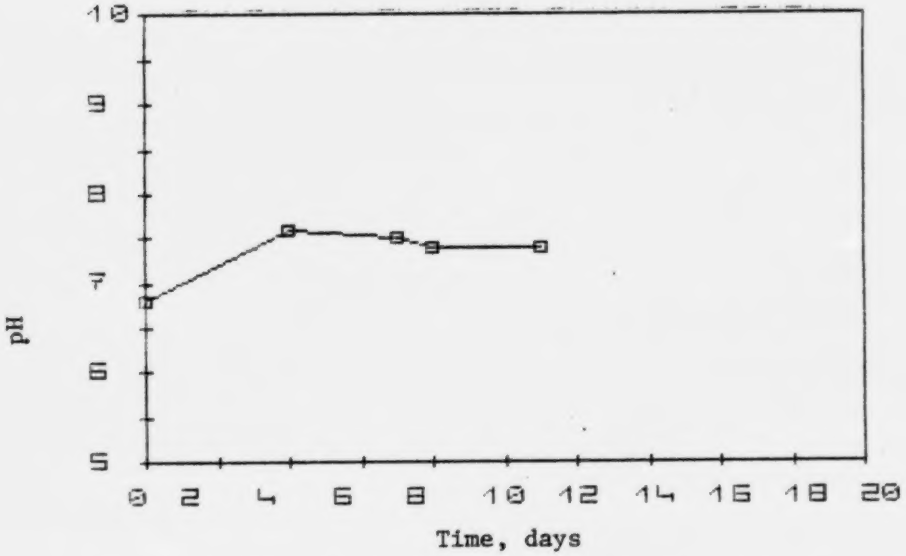


Figure B.108. pH of effluent sewage from third unit in Hanover NFT in Phase 1. First day of analysis was March 2, 1981.

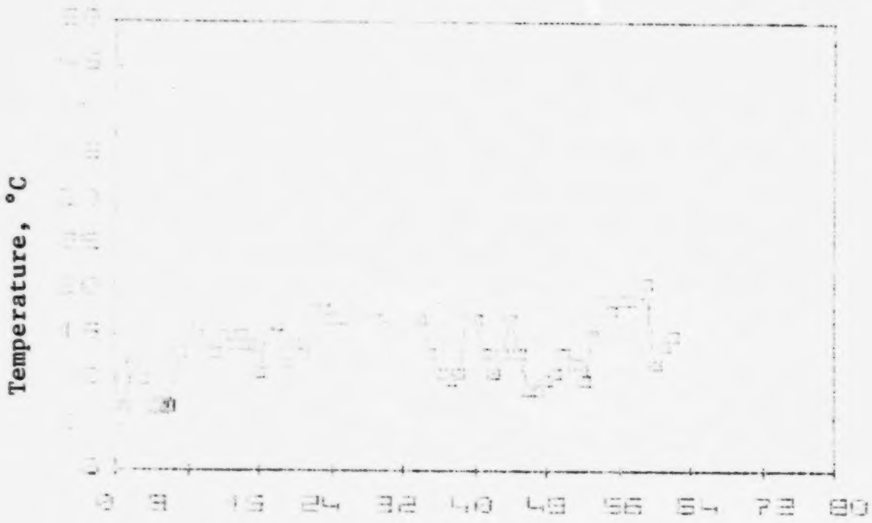


Figure B.109. Minimum daily air temperature in the Hanover NFT greenhouse. First day of measurement was April 2, 1981.

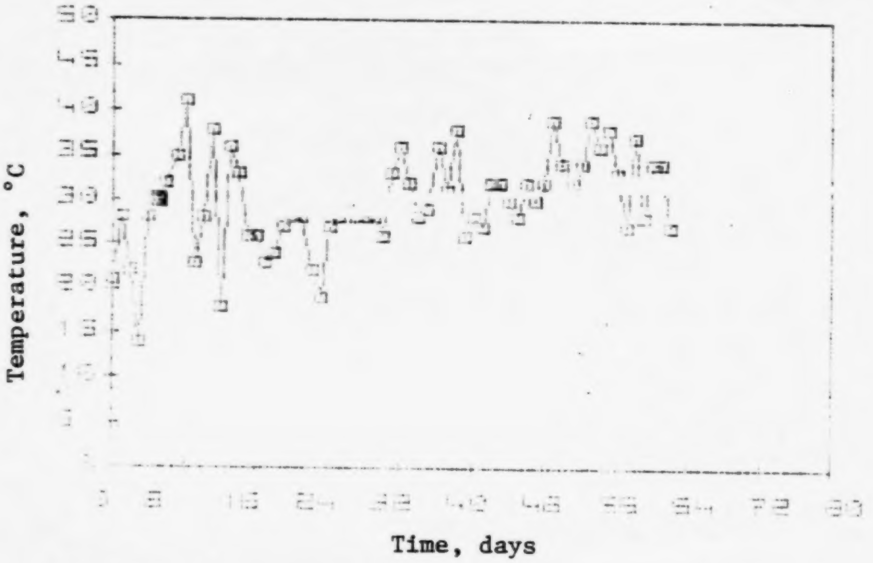


Figure B.110. Maximum daily air temperature in the Hanover NFT greenhouse. First day of measurement was April 2, 1981.

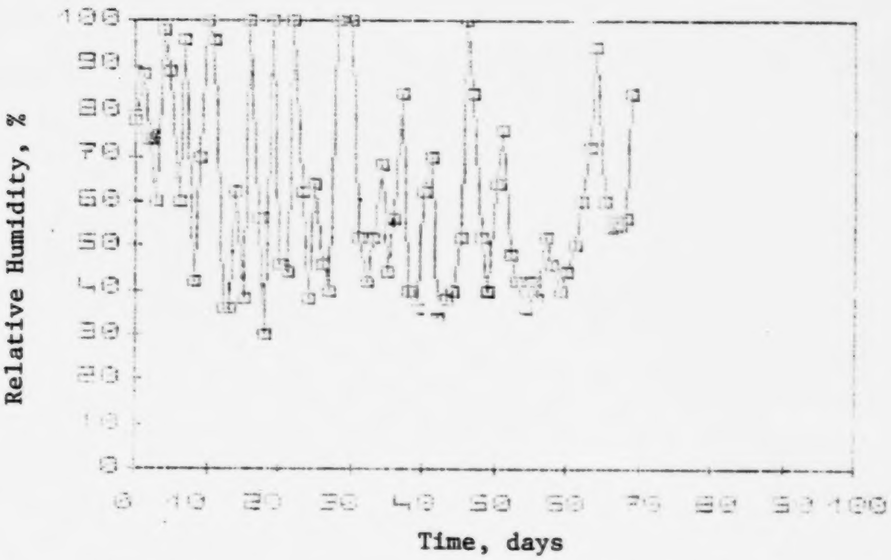


Figure B.111. Minimum daily relative humidity in the Hanover NFT greenhouse. First day of measurement was March 2, 1981.

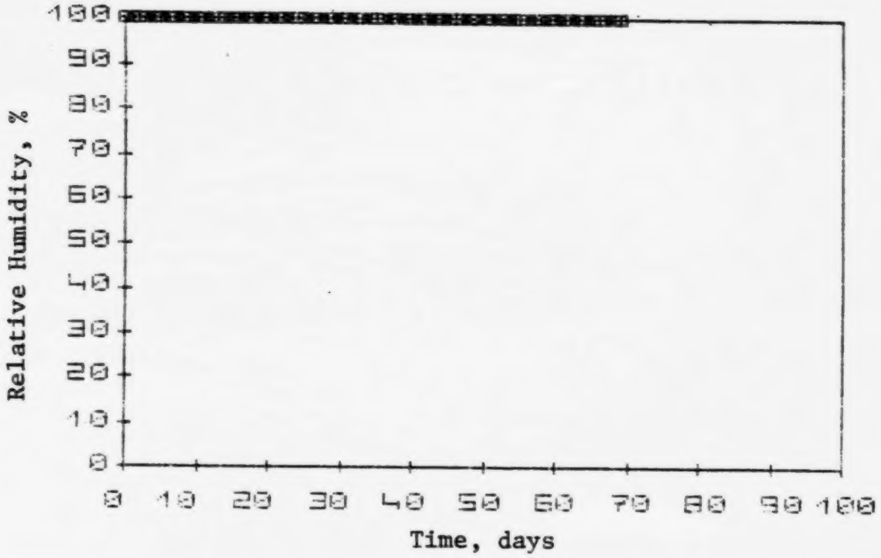


Figure B.112. Maximum daily relative humidity in the Hanover NFT greenhouse. First day of measurement was March 2, 1981.

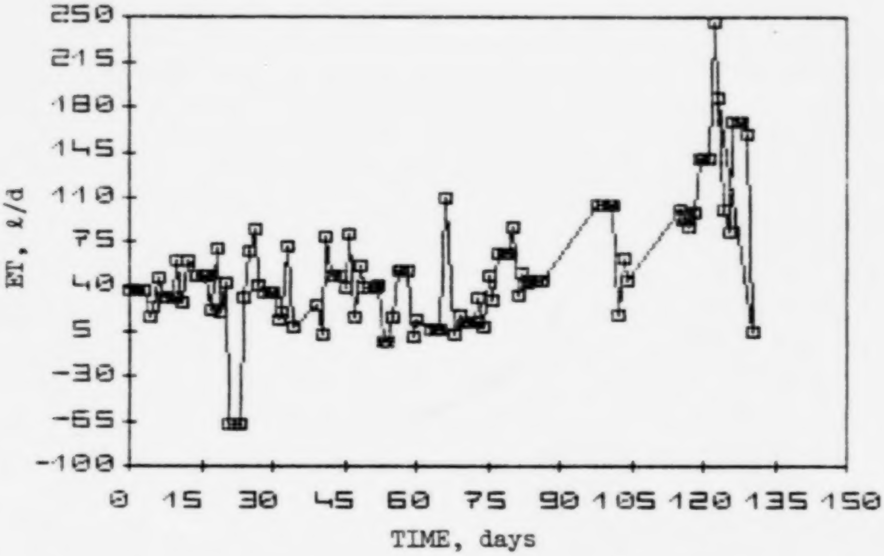


Figure B.113. Evapotranspiration from the Hanover three unit NFT system in Phase 1. First day of measurement was February 26, 1981.

APPENDIX C

This appendix presents data developed at the Cornell University facilities over the course of the project. Tables C.1 through C.25 present mean values of variables over each loading condition tested. The complete data set is presented in three chronological sets. The first set (Figures C.1 to C.98) shows data from the 9.3 m^2 system that was sampled at the influent and effluent stations, as well as intermediate points (noted as points A and B, which were about one-third and two-thirds of the distance through the system, respectively). The second set (Figures C.99 to C.201) shows later experiments using both 9.3 and 18.6 m^2 systems, which were sampled at points identical to those of earlier experiments. In the 18.6 m^2 system the effluent of the first section was the influent to the second section; thus no influent data is shown for the second. The third set (Figures C.202 to C.315) shows experiments in the 27.9 m^2 system, which was made up of three 9.3 m^2 sections connected in series. No intermediate point sampling data was conducted on this large unit. A fuller discussion of test units and loading conditions is presented in Chapter 6, Section A.2.b.

TABLE C.1. LOADING CONDITION PARAMETERS TESTED IN PILOT SCALE NFT SYSTEMS AT CORNELL USING SYNTHETIC WASTEWATER. CONDITION NUMBERS ARE GUIDES TO SPECIFIC VARIABLE DATA WHICH FOLLOWS.

	Target Loading Rate		Condition Dates				
Condition No.	Area Loading Rate cm/d	Weir Loading Rate m^3/m-d	Start	End	System Area m^2	Plant Species	Application Mode
1	10.2	1.24	12/ 6/79	1/ 2/80	9.3	Canary Grass	Continuous
2	10.2	1.24	1/ 3/80	1/27/80	9.3	Canary Grass	30 min on 30 min pause
3	10.2	1.24	1/28/80	2/20/80	9.3	Canary Grass	30 min on 105 min pause
4	10.2	1.24	2/21/80	3/17/80	9.3	Canary Grass	30 min on 90 min pause
5	5.1	0.62	3/18/80	5/11/80	9.3	Canary Grass	Continuous
6	10.2	1.24	5/12/80	6/17/80	9.3	Canary Grass	Continuous
7	5.1	0.62	6/18/80	7/ 3/80	9.3	Canary Grass	Continuous
8	20.3	2.49	7/ 4/80	9/ 8/80	9.3	Canary Grass	Continuous
9	10.2	2.49	9/ 9/80	10/15/80	18.6	Canary Grass	Continuous
10	20.3	4.98	10/16/80	10/31/80	18.6	Canary Grass	Continuous
11	6.9	2.49	2/13/81	3/14/81	27.9	Phragmites* Cucumber† Canary Grass§	Continuous
12	10.2	3.74	4/16/81	5/10/81	27.9	Cattail/Bulrush* Phragmites† Canary Grass§	Continuous
13	20.3	7.47	5/11/81	6/10/81	27.9	Cattail/Bulrush* Phragmites† Canary Grass§	30 min on 30 min pause
14	40.6	14.94	6/11/81	7/ 1/81	27.9	Cattail/Bulrush* Phragmites† Canary Grass§	30 min on 30 min pause
15	6.9	2.49	7/ 2/81	7/30/81	27.9	Cattail/Bulrush* Phragmites† Canary Grass§	Continuous
16	10.2	3.74	7/31/81	8/21/81	27.9	Cattail/Bulrush* Phragmites† Canary Grass§	30 min on 30 min pause

*Unit 1, †Unit 2, §Unit 3.

TABLE C.2. TOTAL CHEMICAL OXYGEN DEMAND CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	412	3	405.0 (16.5)	320.7 (50.8)	235.3 (31.0)	164.7 (24.0)				
2	318	3	313.0 (217.6)	233.0 (113.8)	189.0 (59.1)	165.0 (18.3)				
3	377	4	371.0 (53.9)	323.2 (23.4)	302.0 (50.0)	269.0 (29.5)				
4	407	4	400.2 (40.7)	297.2 (45.4)	237.5 (92.4)	147.2 (26.3)				
5	215	8	423.4 (41.7)	256.4 (37.2)	138.4 (29.3)	55.0 (22.6)				
6	280	5	275.6 (18.6)	161.8 (19.4)	118.0 (31.2)	38.4 (15.7)				
7	133	3	260.7 (64.0)	108.0 (32.1)	77.0 (9.6)	62.3 (16.4)				
8	392	5	192.8 (23.3)	134.4 (10.7)	83.0 (31.3)	62.4 (16.8)				

table continued...

TABLE C.2. continued

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	210	3	207.7 (26.0)	146.3 (21.7)	147.0 (44.8)	31.2 (12.0)	62.7 (2.5)	60.7 (3.4)	19.7 (8.0)	
10	395	4	194 (28)	158 (36)	140 (48)	81 (38)	97 (39)	72 (35)	26 (20)	
11	187	6	275.0 (84.7)	-- --	-- --	156.7 (43.8)	-- --	-- --	103.5 (37.3)	48.3 (48.6)
12	185	4	181.5 (25.8)	-- --	-- --	100.00 (29.7)	-- --	-- --	65.2 (26.7)	46.8 (11.8)
13	348	5	170.8 (41.0)	-- --	-- --	125.8 (67.6)	-- --	-- --	85.6 (37.5)	31.6 (19.3)
14	972	3	238.7 (50.0)	-- --	-- --	242.0 (67.2)	-- --	-- --	215.0 (42.6)	137.0 (15.4)
15	144	2	212.5 (67.2)	-- --	-- --	143.0 (21.2)	-- --	-- --	401.3 (541.0)	144.0 (136.2)
16	460	4	452.2 (115.0)	-- --	-- --	306.7 (90.3)	-- --	-- --	173.3 (97.5)	127.0 (68.6)

TABLE C.3. SOLUBLE CHEMICAL OXYGEN DEMAND CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	412	3	405.0 (18.5)	250.0 (48.7)	222.3 (26.7)	163.7 (34.8)				
2	382	3	375.7 (90.8)	208.0 (127.7)	173.3 (61.2)	175.7 (22.3)				
3	392	4	385.8 (20.7)	324.2 (25.2)	280.2 (48.6)	258.5 (39.7)				
4	382	4	375.8 (24.0)	252.8 (21.7)	158.2 (18.0)	145.5 (26.3)				
5	213	8	419.5 (61.5)	217.9 (44.8)	112.4 (26.7)	62.5 (19.4)				
6	278	5	273.4 (29.5)	134.4 (13.6)	67.8 (6.6)	33.4 (6.9)				
7	128	3	252.3 (59.0)	103.3 (21.2)	53.0 (9.2)	50.0 (24.6)				
8	376	5	184.8 (18.5)	110.8 (11.6)	73.0 (18.5)	62.0 (24.6)				

table continued...

TABLE C.3. continued

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	101	3	99.3 (23.1)	131.7 (22.9)	82.0 (23.6)	50.7 (17.7)	35.3 (12.7)	23.7 (7.1)	13.7 (2.1)	
10	391	4	192 (24)	143 (26)	94 (30)	72 (27)	51 (27)	33 (29)	26 (21)	
11	194	6	286.2 (96.3)	-- --	-- --	174.2 (106.9)	-- --	-- --	106.8 (51.1)	36.3 (28.1)
12	173	4	170.2 (51.4)	-- --	-- --	91.0 (52.1)	-- --	-- --	60.8 (36.5)	41.8 (34.3)
13	375	5	184.4 (56.0)	-- --	-- --	85.2 (49.1)	-- --	-- --	83.6 (42.4)	32.0 (19.2)
14	903	3	222.0 (37.0)	-- --	-- --	246.3 (67.9)	-- --	-- --	178.7 (53.7)	108.7 (17.9)
15	151	2	222.5 (50.2)	-- --	-- --	169.7 (88.7)	-- --	-- --	89.3 (48.8)	74.0 (35.1)
16	390	3	383.7 (122.7)	-- --	-- --	272.3 (142.2)	-- --	-- --	160.7 (103.8)	78.3 (70.0)

TABLE C.4. TOTAL NITROGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	38.7	3	38.0 (4.4)	36.5 (3.1)	35.2 (1.6)	31.4 (4.1)				
2	42.2	3	41.5 (3.4)	33.6 (8.0)	31.6 (6.4)	29.2 (5.0)				
3	34.2	4	33.6 (5.2)	32.5 (6.1)	32.1 (5.5)	33.9 (5.8)				
4	36.3	2	35.7 (3.4)	30.3 (12.3)	28.9 (5.6)	26.2 (2.7)				
5	19.0	6	37.4 (4.1)	36.5 (3.0)	31.6 (6.4)	29.2 (4.1)				
6	41.9	6	41.2 (3.3)	38.6 (4.3)	35.6 (3.7)	31.8 (3.8)				
7	18.8	2	37.0 (1.6)	29.0 (6.9)	21.4 (12.0)	25.2 (0.0)				
8	71.1	5	35.0 (4.9)	32.4 (4.8)	30.0 (3.7)	27.3 (3.4)				

table continued...

TABLE C.4. continued

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	34.1	3	33.6 (8.2)	27.3 (6.6)	26.7 (4.4)	24.1 (3.5)	26.1 (1.2)	27.0 (4.1)	14.4 (9.4)	
10	35.8	4	17.6 (8.8)	33.6 (3.9)	33.8 (4.9)	30.5 (5.0)	31.0 (4.4)	29.8 (2.4)	30.4 (2.8)	
11	26.5	6	39.1 (3.0)	-- --	-- --	34.2 (3.2)	-- --	-- --	32.0 (2.1)	30.4 (2.1)
12	39.7	5	39.0 (6.1)	-- --	-- --	35.1 (5.1)	-- --	-- --	33.4 (5.9)	32.5 (5.9)
13	36.2	6	17.8 (4.0)	-- --	-- --	19.3 (9.3)	-- --	-- --	11.7 (2.6)	11.6 (3.7)
14	140.8	4	34.6 (3.3)	-- --	-- --	35.2 (3.7)	-- --	-- --	35.2 (5.6)	32.6 (3.7)
15	13.3	3	19.6 (11.6)	-- --	-- --	23.3 (10.1)	-- --	-- --	26.9 (10.2)	22.3 (11.2)
16	57.1	3	56.1 (4.6)	-- --	-- --	55.3 (10.1)	-- --	-- --	52.0 (15.3)	51.4 (8.3)

TABLE C.5. SOLUBLE TOTAL NITROGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	38.8	2	38.1 (4.9)	33.8 (4.4)	34.0 (1.5)	28.5 (3.2)				
2	38.4	3	37.7 (2.2)	33.3 (7.0)	30.8 (4.0)	28.8 (4.4)				
3	37.3	4	36.6 (4.3)	33.5 (6.1)	30.4 (5.5)	30.1 (4.6)				
4	38.6	3	37.9 (3.9)	26.8 (7.9)	25.5 (0.4)	26.0 (2.8)				
5	19.3	6	37.9 (5.9)	33.6 (6.7)	31.9 (7.1)	28.8 (3.7)				
6	41.4	6	40.7 (3.2)	34.8 (4.0)	34.1 (5.0)	32.8 (5.9)				
7	18.3	2	36.0 (0.6)	29.9 (4.2)	28.8 (0.0)	21.6 (0.0)				
8	68.5	5	33.7 (4.4)	31.6 (4.9)	28.7 (3.7)	27.2 (3.1)				

table continued...

TABLE C.5. continued

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	37.0	3	36.4 (12.4)	28.4 (6.0)	25.7 (4.1)	22.8 (2.1)	26.8 (4.0)	26.4 (4.2)	23.8 (2.9)	
10	38.3	4	18.8 (7.7)	28.3 (2.6)	29.0 (4.0)	30.3 (4.2)	34.1 (5.1)	29.9 (2.8)	30.8 (0.8)	
11	25.3	6	37.3 (6.0)	-- --	-- --	32.5 (3.4)	-- --	-- --	30.6 (2.1)	29.0 (2.1)
12	37.6	5	37.0 (5.3)	-- --	-- --	30.7 (3.8)	-- --	-- --	29.7 (4.9)	31.1 (5.6)
13	34.8	6	17.1 (3.6)	-- --	-- --	13.6 (4.4)	-- --	-- --	10.3 (2.2)	10.8 (4.0)
14	132.3	4	32.5 (1.6)	-- --	-- --	35.8 (5.3)	-- --	-- --	32.8 (4.1)	32.0 (3.6)
15	11.3	--	16.6 (11.1)	-- --	-- --	19.5 (9.3)	-- --	-- --	19.5 (8.3)	21.1 (8.4)
16	58.6	--	57.6 (5.0)	-- --	-- --	50.3 (8.9)	-- --	-- --	50.9 (8.2)	49.9 (8.4)

TABLE C.6. ORGANIC NITROGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	3	34.6 (3.8)	12.5 (1.1)	5.8 (0.6)	4.3 (1.1)				
2	3	38.1 (3.3)	23.2 (3.9)	10.0 (2.5)	5.3 (0.6)				
3	3	26.1 (3.7)	24.8 (10.0)	23.6 (8.1)	25.6 (9.2)				
4	2	32.9 (1.8)	19.7 (6.8)	10.1 (5.3)	6.7 (1.4)				
5	6	30.6 (6.0)	8.9 (2.5)	5.0 (3.0)	5.1 (2.4)				
6	6	33.6 (5.7)	7.0 (2.7)	3.7 (2.3)	3.7 (3.7)				
7	2	33.3 (0.4)	1.6 (2.6)	0.0 (0.0)	1.1 (0.0)				
8	5	29.9 (5.8)	5.1 (2.2)	2.7 (1.0)	2.1 (0.7)				

table continued...

TABLE C.6. continued

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3 Effluent
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	
9	3	16.3 (1.8)	1.0 (1.0)	0.7 (0.1)	0.3 (0.5)	2.6 (1.3)	2.7 (1.3)	2.3 (1.9)	
10	4	16.9 (9.1)	8.7 (2.5)	6.0 (2.4)	1.3 (1.5)	1.9 (2.0)	2.8 (1.9)	1.9 (2.5)	
11	4	34.3 (8.4)	-- --	-- --	3.2 (0.5)	-- --	-- --	1.8 (0.6)	1.0 (0.7)
12	5	36.6 (7.3)	-- --	-- --	11.7 (1.3)	-- --	-- --	6.6 (1.7)	2.7 (1.2)
13	6	16.9 (3.9)	-- --	-- --	13.8 (9.8)	-- --	-- --	4.2 (2.3)	3.0 (3.7)
14	4	31.1 (3.8)	-- --	-- --	18.0 (2.1)	-- --	-- --	8.7 (3.3)	3.8 (1.1)
15	3	7.9 (5.4)	-- --	-- --	3.6 (3.1)	-- --	-- --	4.8 (2.8)	1.6 (2.3)
16	3	46.7 (3.4)	-- --	-- --	4.9 (1.6)	-- --	-- --	3.2 (1.3)	1.5 (0.6)

TABLE C.7. SOLUBLE ORGANIC NITROGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	2	35.4 (3.9)	9.7 (3.0)	4.6 (0.2)	2.2 (0.3)				
2	3	35.3 (2.7)	17.6 (7.1)	9.0 (5.1)	4.1 (1.0)				
3	3	29.6 (7.4)	23.0 (10.1)	22.7 (8.1)	24.1 (4.1)				
4	2	37.7 (3.0)	9.6 (7.6)	8.1 (3.5)	4.9 (3.4)				
5	6	29.5 (6.0)	5.1 (5.3)	4.1 (4.5)	5.0 (4.3)				
6	6	33.7 (6.1)	3.1 (2.0)	2.5 (2.1)	4.5 (5.4)				
7	2	33.4 (1.3)	2.1 (0.7)	1.1 (0.0)	0.6 (0.0)				
8	5	28.3 (6.0)	4.8 (2.7)	1.8 (0.7)	1.5 (0.6)				

table continued...

TABLE C.7. continued

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	3	16.4 (1.9)	1.7 (0.3)	0.1 (0.1)	0.2 (0.3)	2.1 (1.4)	2.1 (2.1)	1.6 (1.3)	
10	4	18.3 (8.0)	4.2 (1.7)	1.3 (1.5)	1.4 (1.6)	3.9 (5.0)	2.1 (2.4)	1.1 (2.3)	
11	--	32.1 (8.6)	-- --	-- --	3.0 (1.0)	-- --	-- --	1.1 (0.6)	0.6 (0.4)
12	4	33.1 (8.2)	-- --	-- --	10.1 (3.2)	-- --	-- --	3.3 (1.1)	1.7 (0.7)
13	5	15.9 (3.9)	-- --	-- --	8.0 (3.2)	-- --	-- --	2.9 (1.9)	3.6 (6.8)
14	6	28.0 (3.3)	-- --	-- --	11.3 (4.0)	-- --	-- --	5.5 (2.7)	1.9 (1.1)
15	4	5.0 (2.2)	-- --	-- --	0.8 (0.6)	-- --	-- --	1.0 (1.1)	0.8 (0.9)
16	--	49.4 (6.6)	-- --	-- --	2.9 (1.7)	-- --	-- --	2.4 (1.2)	2.1 (0.6)

TABLE C.8. AMMONIUM NITROGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	2	1.2 (1.7)	23.0 (3.2)	28.7 (0.0)	25.6 (3.3)				
2	3	0.9 (0.9)	9.7 (10.8)	21.5 (7.7)	23.7 (4.9)				
3	3	3.7 (1.3)	6.7 (3.9)	8.2 (4.1)	7.4 (4.7)				
4	2	0.7 (1.0)	11.6 (10.2)	17.7 (3.2)	18.9 (1.1)				
5	8	8.1 (7.8)	26.2 (4.6)	24.9 (6.0)	22.9 (5.0)				
6	6	7.6 (6.4)	31.6 (2.7)	32.0 (1.9)	28.0 (3.2)				
7	3	2.4 (2.3)	20.7 (12.0)	17.2 (10.5)	12.0 (12.0)				
8	5	5.1 (1.8)	27.3 (3.8)	27.3 (3.6)	25.2 (3.2)				

table continued...

TABLE C.8. continued

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	3	13.1 (11.5)	29.9 (3.2)	31.0 (4.7)	27.5 (5.2)	32.4 (7.6)	26.5 (3.6)	23.0 (4.3)	
10	4	0.6 (1.3)	24.9 (2.5)	27.7 (3.0)	29.2 (3.5)	28.9 (4.2)	27.0 (2.6)	28.5 (3.6)	
11	6	4.0 (5.5)	-- --	-- --	31.0 (3.0)	-- --	-- --	29.8 (2.6)	29.2 (2.5)
12	5	2.4 (1.4)	-- --	-- --	23.4 (5.5)	-- --	-- --	26.8 (4.9)	29.8 (4.7)
13	6	0.9 (1.0)	-- --	-- --	5.2 (2.8)	-- --	-- --	7.4 (2.7)	8.7 (2.3)
14	4	3.5 (1.8)	-- --	-- --	21.2 (3.4)	-- --	-- --	28.4 (3.0)	31.3 (3.3)
15	4	15.0 (10.8)	-- --	-- --	21.4 (8.0)	-- --	-- --	22.7 (6.3)	21.5 (7.5)
16	4	7.7 (6.6)	-- --	-- --	47.8 (9.9)	-- --	-- --	47.0 (8.9)	46.5 (9.2)

TABLE C.9. SOLUBLE AMMONIUM NITROGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	1	0.4 (0.0)	23.5 (1.4)	28.1 (0.0)	24.2 (0.0)				
2	3	0.6 (0.6)	14.3 (13.9)	23.0 (9.9)	24.6 (4.7)				
3	3	3.7 (3.7)	10.5 (6.2)	7.1 (4.1)	5.4 (2.4)				
4	2	0.6 (0.8)	18.3 (7.1)	17.1 (3.5)	20.5 (0.9)				
5	8	9.8 (10.5)	27.4 (4.1)	26.7 (5.0)	23.1 (5.7)				
6	6	7.0 (5.5)	32.6 (4.1)	31.6 (3.4)	27.6 (3.7)				
7	3	1.7 (1.6)	20.9 (12.3)	22.1 (7.9)	11.9 (10.8)				
8	4	5.4 (1.9)	26.6 (4.0)	27.1 (3.2)	25.6 (3.4)				

table continued...

TABLE C.9. continued

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	3	13.3 (11.8)	29.9 (3.3)	30.4 (3.7)	26.5 (6.2)	32.7 (5.8)	27.2 (3.1)	23.9 (2.3)	
10	4	0.4 (0.9)	24.1 (1.0)	27.7 (2.6)	28.9 (2.8)	30.2 (2.0)	26.7 (1.2)	28.7 (2.7)	
11	6	3.6 (5.1)	-- --	-- --	29.9 (2.8)	-- --	-- --	29.5 (2.2)	28.3 (2.2)
12	5	3.9 (4.5)	-- --	-- --	20.6 (2.8)	-- --	-- --	26.5 (4.6)	29.3 (5.1)
13	6	1.1 (0.9)	-- --	-- --	55.8 (1.7)	-- --	-- --	7.4 (2.7)	8.7 (2.3)
14	4	3.4 (2.0)	-- --	-- --	20.3 (3.8)	-- --	-- --	27.3 (1.8)	30.2 (4.0)
15	4	14.4 (9.5)	-- --	-- --	19.9 (8.0)	-- --	-- --	19.3 (6.7)	20.7 (6.3)
16	4	7.1 (8.3)	-- --	-- --	45.2 (8.2)	-- --	-- --	46.7 (6.9)	44.7 (8.9)

TABLE C.10. TOTAL KJELDAHL NITROGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	3	35.9 (4.0)	36. (3.2)	35.1 (1.6)	31.4 (4.2)				
2	3	39.1 (3.0)	32.9 (8.0)	31.4 (6.2)	29.1 (5.0)				
3	4	32.5 (6.5)	32.7 (6.3)	32.1 (4.7)	33.0 (5.0)				
4	2	33.6 (2.8)	31.3 (1.1)	27.8 (4.5)	25.6 (2.3)				
5	6	37.4 (4.1)	36.5 (3.0)	31.6 (6.4)	29.2 (4.1)				
6	6	41.2 (3.3)	38.6 (4.3)	35.6 (3.7)	31.8 (3.8)				
7	2	37.0 (1.6)	29.0 (6.9)	21.4 (12.0)	25.2 --				
8	5	35.0 (4.9)	32.4 (4.8)	30.0 (3.7)	27.3 (3.4)				

table continued...

TABLE C.10. continued

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	3	16.3 (1.8)	1.0 (1.0)	0.7 (0.1)	0.4 (0.5)	2.1 (0.7)	2.1 (1.3)	1.5 (1.9)	-- --
10	--								
11	5	38.6 (3.1)	-- --	-- --	33.8 (3.4)	-- --	-- --	32.3 (2.1)	30.2 (2.3)
12	5	36.6 (7.3)	-- --	-- --	11.7 (1.3)	-- --	-- --	6.6 (1.7)	2.7 (1.2)
13	6	16.9 (3.9)	-- --	-- --	13.8 (9.8)	-- --	-- --	4.2 (2.3)	3.0 (3.7)
14	4	34.6 (3.3)	-- --	-- --	39.3 (5.4)	-- --	-- --	37.0 (4.1)	35.1 (3.6)
15	3	19.6 (11.5)	-- --	-- --	23.3 (10.1)	-- --	-- --	26.9 (10.2)	22.3 (1.1)
16	3	56.1 (4.6)	-- --	-- --	55.3 (10.1)	-- --	-- --	52.0 (15.3)	51.4 (8.3)

TABLE C.11. SOLUBLE TOTAL KJELDAHL NITROGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	2	36.1 (4.4)	33.5 (4.2)	33.7 (1.2)	28.4 (3.2)				
2	3	35.9 (2.3)	31.8 (6.9)	30.4 (4.4)	28.7 (4.4)				
3	4	35.1 (4.7)	34.0 (5.0)	29.8 (6.2)	29.5 (4.9)				
4	2	38.2 (2.2)	27.8 (6.4)	23.3 (3.2)	25.4 (2.5)				
5	6	37.9 (5.9)	33.6 (6.7)	31.9 (7.2)	28.8 (3.7)				
6	6	40.7 (3.2)	34.8 (4.0)	34.1 (5.0)	32.8 (5.9)				
7	2	36.0 (0.6)	29.8 (4.2)	28.8 --	21.6 --				
8	5	33.7 (5.2)	31.6 (4.9)	28.7 (3.7)	27.2 (3.1)				

table continued...

TABLE C.11. continued

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	3	16.4 (1.9)	1.7 (0.3)	0.1 (0.2)	0.2 (0.4)	1.8 (1.2)	1.8 (1.6)	1.0 (1.3)	-- --
10	--								
11	5	36.3 (6.1)	-- --	-- --	33.1 (3.6)	-- --	-- --	30.7 (2.2)	29.1 (2.4)
12	5	33.1 (8.2)	-- --	-- --	10.1 (3.2)	-- --	-- --	3.3 (1.1)	1.7 (0.7)
13	6	15.9 (3.9)	-- --	-- --	8.0 (3.2)	-- --	-- --	2.9 (1.9)	3.6 (6.8)
14	4	32.5 (1.6)	-- --	-- --	35.9 (5.3)	-- --	-- --	32.8 (4.1)	32.1 (3.6)
15	4	19.4 (10.6)	-- --	-- --	20.8 (8.0)	-- --	-- --	20.3 (7.0)	21.5 (6.9)
16	3	57.6 (5.0)	-- --	-- --	50.3 (8.9)	-- --	-- --	50.6 (8.7)	49.9 (8.3)

TABLE C.12. NITRATE NITROGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	--	2.1 (0.6)	0.3 (0.3)	0.0 (0.0)	0.0 (0.1)				
2	--	2.1 (0.8)	0.7 (0.2)	0.1 (0.2)	0.1 (0.2)				
3	--	1.5 (1.5)	1.3 (1.6)	0.7 (0.7)	1.3 (1.0)				
4	--	2.3 (0.6)	1.1 (0.9)	0.7 (0.6)	0.6 (0.5)				
5	--	2.5 (0.9)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)				
6	4	3.7 (2.1)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)				
7	--								
8	--								
9	--								
10	--								
11	--								
12	--								
13	--								
14	--								
15	--								
16	--								

TABLE C.13. SOLUBLE NITRATE NITROGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	--	2.3 (0.6)	0.5 (0.4)	0.1 (0.2)	0.0 (0.0)				
2	--	1.8 (0.2)	1.4 (0.3)	0.3 (0.5)	0.1 (0.2)				
3	--	2.0 (2.1)	0.4 (0.6)	1.1 (1.0)	0.6 (1.0)				
4	--	2.0 (0.3)	2.7 (2.9)	0.7 (0.8)	0.7 (0.6)				
5	--	2.6 (1.2)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)				
6	4	3.4 (1.8)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)				
7	--								
8	--								
9	--								
10	--								
11	--								
12	--								
13	--								
14	--								
15	--								
16	--								

TABLE C.14. TOTAL PHOSPHORUS CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	17.7	2	17.4 (0.9)	16.4 (0.8)	17.2 (0.6)	16.3 (1.6)				
2	13.5	3	13.3 (0.9)	8.0 (2.4)	9.2 (2.2)	9.5 (2.5)				
3	16.2	4	15.9 (0.3)	16.0 (0.9)	14.7 (1.4)	14.8 (0.5)				
4	13.7	3	13.5 (1.2)	13.0 (1.7)	11.0 (1.4)	12.1 (1.5)				
5	7.2	8	14.2 (1.8)	14.2 (1.7)	13.2 (2.1)	13.3 (2.8)				
6	14.1	6	13.9 (1.8)	14.4 (1.6)	13.5 (1.8)	13.9 (3.0)				
7	7.2	3	14.1 (1.1)	10.8 (3.7)	9.5 (6.4)	6.6 (6.1)				
8	29.5	5	14.5 (2.4)	14.7 (2.3)	14.9 (2.8)	14.8 (2.4)				

table continued...

TABLE C.14. continued

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	13.5	3	13.3 (3.0)	11.6 (1.3)	11.6 (1.4)	12.9 (3.0)	11.0 (3.0)	10.0 (4.0)	10.1 (4.6)	
10	27.7	4	13.6 (1.3)	12.8 (1.6)	12.7 (2.0)	13.5 (1.8)	12.3 (2.2)	13.8 (1.8)	13.1 (2.4)	
11	10.7	6	15.8 (3.7)	-- --	-- --	15.6 (3.2)	-- --	-- --	14.6 (2.9)	15.4 (3.8)
12	12.3	5	12.1 (2.8)	-- --	-- --	11.8 (3.4)	-- --	-- --	11.3 (3.4)	11.2 (2.6)
13	12.2	5	6.0 (1.5)	-- --	-- --	5.6 (1.6)	-- --	-- --	4.9 (1.5)	5.4 (1.7)
14	45.6	4	11.2 (5.2)	-- --	-- --	12.6 (2.8)	-- --	-- --	12.7 (1.1)	12.7 (3.1)
15	5.7	4	8.4 (4.8)	-- --	-- --	7.6 (2.7)	-- --	-- --	8.2 (3.2)	8.9 (2.3)
16	--	3	14.7 (3.0)	-- --	-- --	15.0 (1.7)	-- --	-- --	18.2 (2.6)	15.5 (4.6)

TABLE C.15. SOLUBLE PHOSPHORUS CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations		Unit 1				Unit 2		Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	16.9	2	16.6 (2.1)	16.6 (0.4)	15.4 (2.8)	16.4 (1.7)				
2	10.9	3	10.7 (4.9)	10.5 (2.8)	9.3 (2.1)	9.5 (1.4)				
3	16.0	4	15.7 (1.9)	14.8 (0.9)	14.9 (1.0)	14.5 (0.7)				
4	14.3	3	14.1 (0.3)	12.6 (0.9)	13.1 (2.3)	11.9 (2.3)				
5	7.2	8	14.2 (1.6)	14.3 (1.6)	13.7 (2.7)	12.8 (2.6)				
6	15.1	6	14.8 (1.1)	15.8 (2.3)	14.1 (1.5)	13.6 (2.0)				
7	7.4	3	14.5 (1.7)	11.5 (3.9)	8.4 (5.2)	7.0 (6.3)				
8	29.3	5	14.4 (3.1)	14.5 (2.3)	15.0 (2.6)	15.0 (2.2)				

table continued...

TABLE C.15. continued

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	9.9	3	9.7 (2.9)	12.8 (0.7)	12.7 (3.0)	12.5 (3.6)	10.6 (2.1)	10.8 (4.8)	10.2 (5.1)	
10	27.1	4	13.3 (1.7)	12.4 (1.2)	14.1 (3.4)	14.1 (2.0)	12.1 (1.8)	13.2 (1.4)	13.2 (2.5)	
11	11.3	6	16.6 (3.4)	-- --	-- --	16.0 (3.1)	-- --	-- --	15.0 (2.7)	15.2 (4.1)
12	13.4	5	13.2 (2.5)	-- --	-- --	11.3 (2.8)	-- --	-- --	11.5 (4.4)	10.9 (4.2)
13	12.0	-	5.9 (1.3)	-- --	-- --	5.6 (0.8)	-- --	-- --	4.9 (1.4)	5.7 (1.5)
14	50.1	4	12.3 (6.1)	-- --	-- --	13.3 (2.9)	-- --	-- --	12.9 (4.5)	12.8 (1.9)
15	6.2	4	9.2 (3.4)	-- --	-- --	8.4 (3.3)	-- --	-- --	9.9 (2.5)	9.8 (2.8)
16	16.9	3	16.6 (4.3)	-- --	-- --	17.4 (0.6)	-- --	-- --	16.2 (5.4)	16.5 (2.0)

TABLE C.16. pH AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	3	6.3 (0.2)	6.6 (0.0)	6.8 (0.2)	6.9 (0.1)				
2	3	6.6 (0.4)	6.6 (0.3)	6.7 (0.2)	6.9 (0.2)				
3	4	6.7 (0.1)	6.8 (0.0)	6.9 (0.1)	7.0 (0.2)				
4	4	6.5 (0.2)	6.5 (0.2)	6.6 (0.3)	6.9 (0.2)				
5	6	6.3 (0.2)	6.5 (0.1)	6.8 (0.2)	7.1 (0.1)				
6	5	6.8 (0.1)	7.0 (0.1)	7.2 (0.1)	7.4 (0.1)				
7	3	7.1 (0.3)	7.1 (0.2)	7.3 (0.1)	7.4 (0.2)				
8	6	6.9 (0.1)	7.0 (0.2)	7.1 (0.1)	7.2 (0.2)				

table continued...

TABLE C.16. continued

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	4	6.8 (0.2)	7.0 (0.2)	7.2 (0.2)	7.3 (0.2)	7.3 (0.1)	7.3 (0.1)	7.3 (0.1)	
10	3	6.5 (0.2)	6.5 (0.1)	6.8 (0.1)	6.9 (0.1)	7.0 (0.1)	7.1 (0.1)	7.2 (0.2)	
11	5	6.6 (0.2)	-- --	-- --	6.8 (0.1)	-- --	-- --	7.0 (0.2)	7.1 (0.2)
12	4	7.0 (0.2)	-- --	-- --	7.4 (0.3)	-- --	-- --	7.8 (0.2)	7.8 (0.2)
13	6	7.1 (0.1)	-- --	-- --	6.9 (0.2)	-- --	-- --	7.5 (0.1)	7.7 (0.1)
14	4	7.0 (0.1)	-- --	-- --	6.9 (0.2)	-- --	-- --	7.4 (0.1)	7.6 (0.1)
15	4	6.9 (0.2)	-- --	-- --	7.6 (0.1)	-- --	-- --	7.8 (0.1)	7.9 (0.1)
16	3	6.8 (0.2)	-- --	-- --	7.7 (0.2)	-- --	-- --	7.9 (0.1)	8.0 (0.1)

TABLE C.17. FILTERED pH AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	--								
2	--								
3	--								
4	--								
5	6	6.5 (0.3)	6.7 (0.1)	7.1 (0.2)	7.2 (0.1)				
6	5	7.0 (0.1)	7.1 (0.0)	7.5 (0.1)	7.4 (0.1)				
7	3	7.2 (0.1)	7.2 (0.2)	7.4 --	7.3 (0.1)				
8	5	6.8 (0.3)	7.3 (0.2)	7.2 (0.2)	7.3 (0.1)				

table continued...

TABLE C.17. continued

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	4	6.8 (0.1)	7.1 (0.2)	7.3 (0.1)	7.3 (0.1)	7.3 (0.1)	7.3 (0.1)	7.2 (0.1)	
10	3	6.6 (0.2)	7.0 (0.3)	7.0 (0.1)	7.1 (0.2)	7.2 (0.3)	7.2 (0.2)	7.2 (0.2)	
11	--	6.8 (0.2)	-- --	-- --	7.0 (0.2)	-- --	-- --	7.2 (0.2)	7.2 (0.1)
12	--	7.2 (0.2)	-- --	-- --	7.9 (0.5)	-- --	-- --	8.3 (0.3)	8.3 (0.3)
13	--	7.2 (0.2)	-- --	-- --	7.5 (0.4)	-- --	-- --	8.0 (0.2)	8.2 (0.2)
14	--	7.1 (0.1)	-- --	-- --	7.4 (0.5)	-- --	-- --	8.0 (0.3)	8.0 (0.1)
15	3	7.4 (0.2)	-- --	-- --	8.0 (0.4)	-- --	-- --	8.4 (0.4)	8.1 (0.2)
16	3	7.1 (0.1)	-- --	-- --	8.1 (0.1)	-- --	-- --	8.3 (0.1)	8.3 (0.1)

TABLE C.18. DISSOLVED OXYGEN CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	4	8.47 (1.0)	0.8 (0.4)	0.03 (0.06)	2.35 (1.18)				
2	3	10.2 (0.5)	3.9 (0.7)	1.22 (0.79)	2.08 (1.05)				
3	2	10.5 (1.3)	3.7 (1.0)	3.10 (2.68)	3.20 (2.54)				
4	1	7.5 --	4.0 --	1.2 --	2.60 --				
5	9	8.0 (1.2)	0.2 (0.3)	0.2 (0.4)	4.7 (2.1)				
6	--								
7	4	7.2 (1.3)	1.8 (1.3)	3.5 (1.8)	7.0 (0.9)				
8	--								
9	--								
10	--								
11	4	7.6 (0.6)	1.0 (0.6)	0.4 (0.1)	1.0 (1.2)	1.2 (1.5)	0.4 (0.2)	2.8 (1.7)	5.6 (0.6)
12	--								
13	--								
14	--								
15	--								
16	--								

TABLE C.19. TOTAL SOLIDS CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	3	660.0 (45.8)	450.0 (130.0)	786.7 (706.1)	393.3 (51.3)				
2	4	652.5 (60.8)	497.5 (22.2)	425.0 (31.1)	380.0 (38.3)				
3	4	642.5 (86.6)	630.0 (73.5)	572.5 (64.0)	570.0 (60.6)				
4	3	723.3 (49.3)	703.3 (317.8)	560.0 (98.5)	443.3 (25.2)				
5	8	616.2 (160.0)	530.0 (169.4)	311.2 (107.0)	358.8 (79.7)				
6	--								
7	--								
8	--								
9	--								
10	--								
11	6	428.3 (40.7)	-- --	-- --	440.0 (427.0)	-- --	-- --	258.3 (66.2)	253.3 (30.1)
12	5	420.0 (40.6)	-- --	-- --	338.0 (44.9)	-- --	-- --	388.0 (179.6)	278.0 (99.6)
13	3	383.3 (141.5)	-- --	-- --	336.7 (176.0)	-- --	-- --	240.0 (88.9)	233.3 (76.4)
14	--								
15	--								
16	--								

TABLE C.20. TOTAL VOLATILE SOLIDS CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	3	433.3 (41.6)	223.3 (124.2)	580.0 (711.9)	176.7 (25.2)				
2	4	450.0 (62.7)	290.0 (21.6)	202.5 (9.6)	160.0 (31.6)				
3	4	427.5 (58.5)	410.0 (59.4)	360.0 (61.6)	350.0 (58.9)				
4	3	476.7 (35.1)	450.0 (315.7)	310.0 (69.3)	193.3 (37.9)				
5	8	452.5 (90.4)	390.0 (182.0)	173.8 (82.3)	215.7 (60.0)				
6	--								
7	--								
8	--								
9	--								
10	--								
11	6	238.3 (45.4)	-- --	-- --	235.0 (435.0)	-- --	-- --	90.0 (34.6)	81.7 (36.0)
12	3	213.3 (11.5)	-- --	-- --	133.3 (11.5)	-- --	-- --	150.0 (46.9)	110.0 (17.3)
13	4	207.5 (66.5)	-- --	-- --	160.0 (42.4)	-- --	-- --	120.5 (5.0)	87.5 (23.6)
14	4	120.0 (51.6)	-- --	-- --	127.5 (60.2)	-- --	-- --	105.0 (61.4)	67.5 (38.6)
15	4	110.0 (21.6)	-- --	-- --	127.5 (79.3)	-- --	-- --	182.5 (29.8)	220.0 (89.1)
16	4	445.0 (242.8)	-- --	-- --	176.7 (110.2)	-- --	-- --	187.5 (164.4)	110.0 (106.8)

TABLE C.21. SUSPENDED SOLIDS CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	3	2.7 (2.3)	21.3 (7.6)	20.7 (11.4)	5.3 (4.2)				
2	4	4.0 (2.8)	27.8 (7.5)	11.0 (6.8)	9.5 (4.1)				
3	4	2.0 (2.8)	10.5 (4.1)	11.0 (10.1)	12.0 (7.8)				
4	4	1.0 (1.1)	11.5 (3.4)	22.0 (10.6)	11.5 (5.5)				
5	8	4.5 (5.2)	14.2 (4.6)	14.0 (5.3)	7.8 (4.8)				
6	--								
7	--								
8	--								
9	--								
10	--								
11	6	4.3 (2.0)	-- --	-- --	7.7 (3.0)	-- --	-- --	6.8 (1.8)	8.0 (10.1)
12	4	7.0 (4.8)	-- --	-- --	21.0 (14.1)	-- --	-- --	14.0 (6.9)	9.5 (6.4)
13	3	8.0 (3.5)	-- --	-- --	17.7 (7.6)	-- --	-- --	10.0 (6.0)	8.0 (5.3)
14	3	5.3 (2.3)	-- --	-- --	17.7 (15.0)	-- --	-- --	13.3 (8.6)	11.7 (5.5)
15	--								
16	5	11.2 (6.8)	-- --	-- --	33.8 (25.8)	-- --	-- --	53.3 (14.0)	40.4 (15.7)

TABLE C.22. VOLATILE SUSPENDED SOLIDS CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	3	2.7 (2.3)	21.3 (7.6)	18.0 (8.7)	5.3 (4.2)				
2	4	2.0 --	21.7 (8.5)	7.2 (5.7)	8.0 (2.8)				
3	4	1.5 (1.9)	9.5 (3.4)	10.0 (8.2)	11.0 (6.8)				
4	4	0.5 (1.0)	7.0 (6.2)	14.5 (5.0)	8.5 (4.1)				
5	8	4.0 (4.7)	13.2 (4.3)	12.8 (5.4)	6.5 (4.2)				
6	--								
7	--								
8	--								
9	--								
10	--								
11	6	3.7 (0.8)	-- --	-- --	6.3 (3.0)	-- --	-- --	6.0 (2.0)	2.0 (2.0)
12	4	5.5 (3.0)	-- --	-- --	17.5 (15.3)	-- --	-- --	9.5 (5.0)	8.5 (5.3)
13	4	4.5 (2.5)	-- --	-- --	17.8 (10.4)	-- --	-- --	14.2 (7.0)	9.8 (6.6)
14	3	4.7 (3.0)	-- --	-- --	13.0 (10.4)	-- --	-- --	12.3 (8.5)	9.3 (4.2)
15	3	44.7 (7.7)	-- --	-- --	9.3 (13.6)	-- --	-- --	14.5 (20.5)	5.3 (9.2)
16	3	6.3 (3.5)	-- --	-- --	20.2 (15.6)	-- --	-- --	37.3 (16.8)	24.5 (13.2)

TABLE C.23. ZINC CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Number of Determinations	Unit 1				Unit 2			Unit 3
		Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	--								
2	--								
3	--								
4	--								
5	8	0.76 (0.25)	0.21 (0.05)	0.14 (0.11)	0.09 (0.01)				
6	4	0.35 --	0.17 --	0.11 --	0.10 --				
7	--								
8	--								
9	--								
10	--								
11	--								
12	--								
13	--								
14	--								
15	--								
16	--								

TABLE C.24. CADMIUM CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	.112	3	0.11 (0.03)	0.04 (0.02)	0.02 (0.01)	0.02 (0.02)				
2	.112	3	0.11 (0.03)	0.07 (0.02)	0.02 (0.02)	0.01 (0.01)				
3	.061	1	0.06 --	0.05 --	0.06 --	0.02 --				
4	--	--								
5	.168	6	0.33 (0.24)	0.10 (0.02)	0.06 (0.01)	0.05 (0.02)				
6	.214	6	0.21 (0.06)	0.10 (0.04)	0.06 (0.01)	0.05 (0.01)				
7	.076	4	0.15 (0.04)	0.08 (0.02)	0.06 (0.02)	0.06 (0.02)				
8	.305	8	0.15 (0.03)	0.12 (0.03)	0.10 (0.03)	0.09 (0.03)				

table continued...

TABLE C.24. continued

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
9	.193	5	0.19 (0.15)	0.13 (0.05)	0.10 (0.04)	0.09 (0.04)				
		4					0.08 (0.04)	0.07 (0.03)	0.06 (0.04)	
10	.509	3	0.25 (0.11)	0.15 (0.08)	0.12 (0.05)	0.11 (0.06)	0.10 (0.06)	0.10 (0.05)	0.11 (0.06)	
11	.020	6	0.03 (0.02)	-- --	-- --	0.01 (0.02)	-- --	-- --	0.01 (0.02)	0.003 (0.01)
12	.183	5	0.18 (0.04)	-- --	-- --	0.14 (0.04)	-- --	-- --	0.10 (0.03)	0.05 (0.01)
13	.122	5	0.06 (0.03)	-- --	-- --	0.04 (0.01)	-- --	-- --	0.02 (0.01)	0.02 (0.02)
14	--	--								
15	--	--								
16	--	--								

TABLE C.24. SOLUBLE CADMIUM CONCENTRATIONS (mg/ℓ) AT VARIOUS POINTS IN THE CORNELL BRACEHOUSE PILOT SYSTEMS USING SYNTHETIC WASTEWATER. STANDARD DEVIATIONS ARE SHOWN IN PARENTHESES.

Condition Number	Actual Mass Loading Rate kg/ha-d	No. of Determinations	Unit 1				Unit 2			Unit 3
			Influent	Point A	Point B	Effluent	Point A	Point B	Effluent	Effluent
1	--	--								
2	--	--								
3	--	--								
4	--	--								
5	--	--								
6	--	--								
7	--	--								
8	--	--								
9	--	--								
10	--	--								
11	.014	6	0.02 (0.02)	-- --	-- --	0.01 (0.01)	-- --	-- --	0.01 (0.01)	0.01 (0.01)
12	.173	5	0.17 (0.05)	-- --	-- --	0.09 (0.05)	-- --	-- --	0.04 (0.01)	0.03 (0.02)
13	.122	5	0.06 (0.01)	-- --	-- --	0.03 (0.01)	-- --	-- --	0.02 (0.02)	0.01 (0.01)
14	--									
15	--									
16	--									

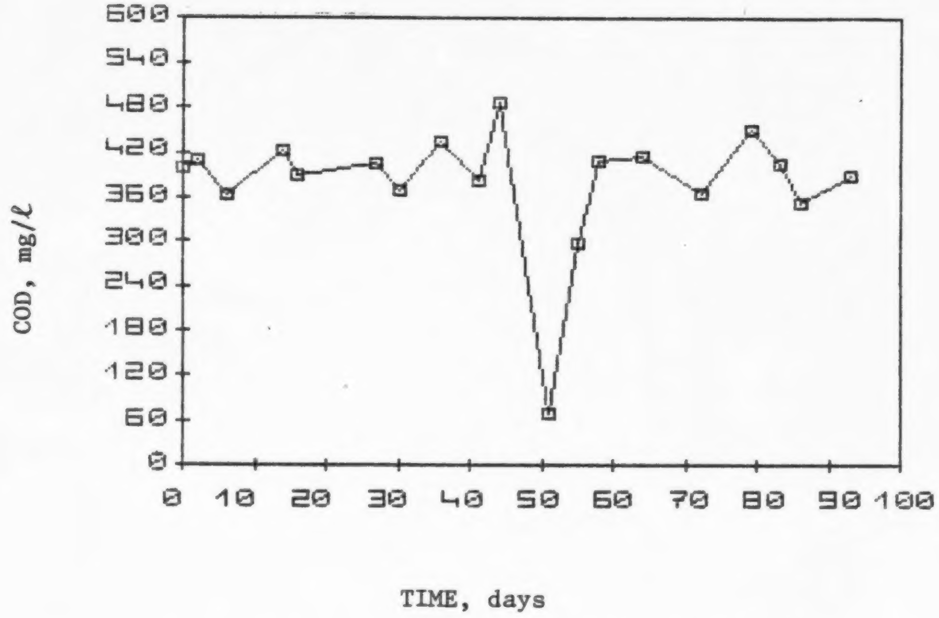


Figure C.1 Chemical oxygen demand concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

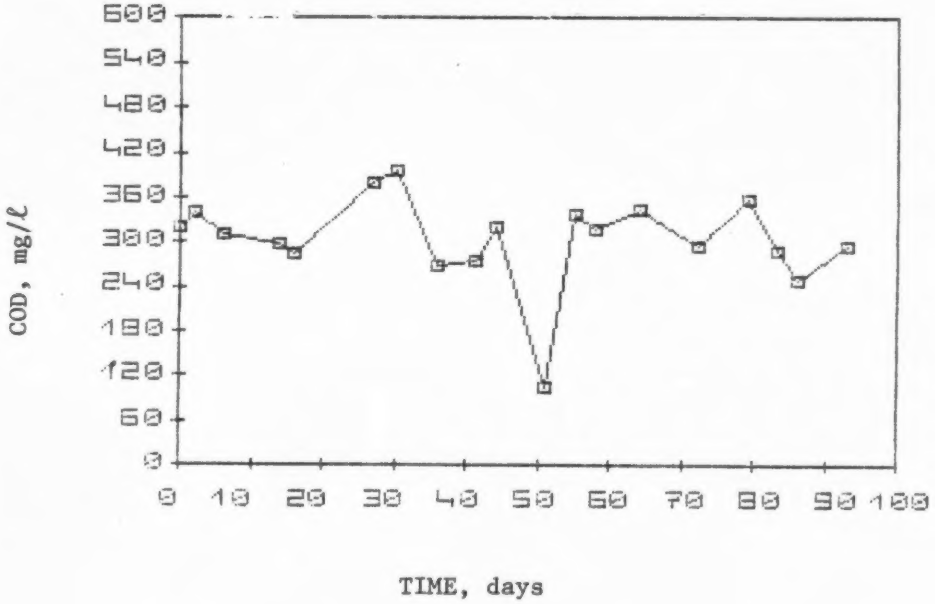


Figure C.2 Chemical oxygen demand concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

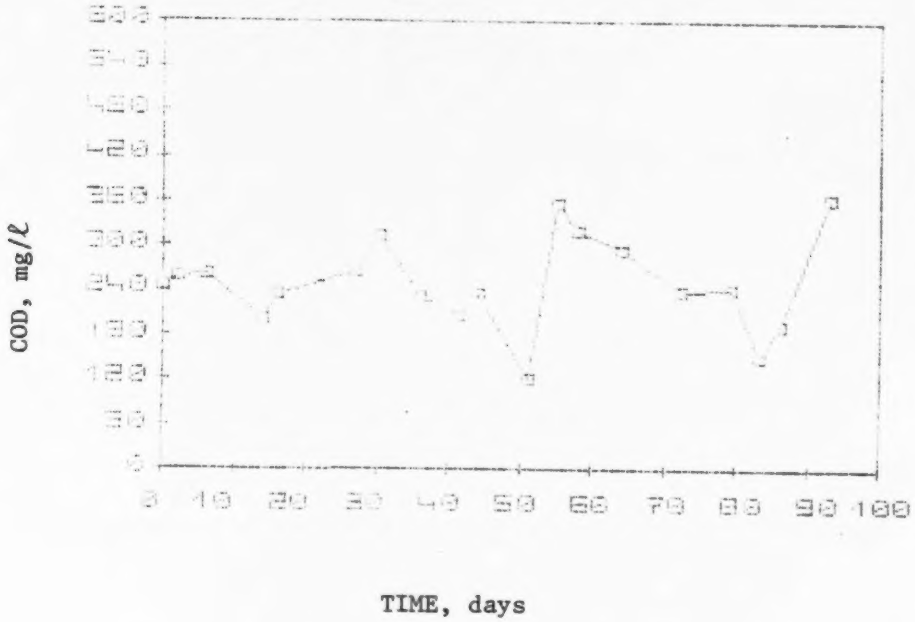


Figure C.3 Chemical oxygen demand concentration of synthetic sewage at Point B in the Cornell NFT in PEase 0. First day of analysis was December 5, 1979.

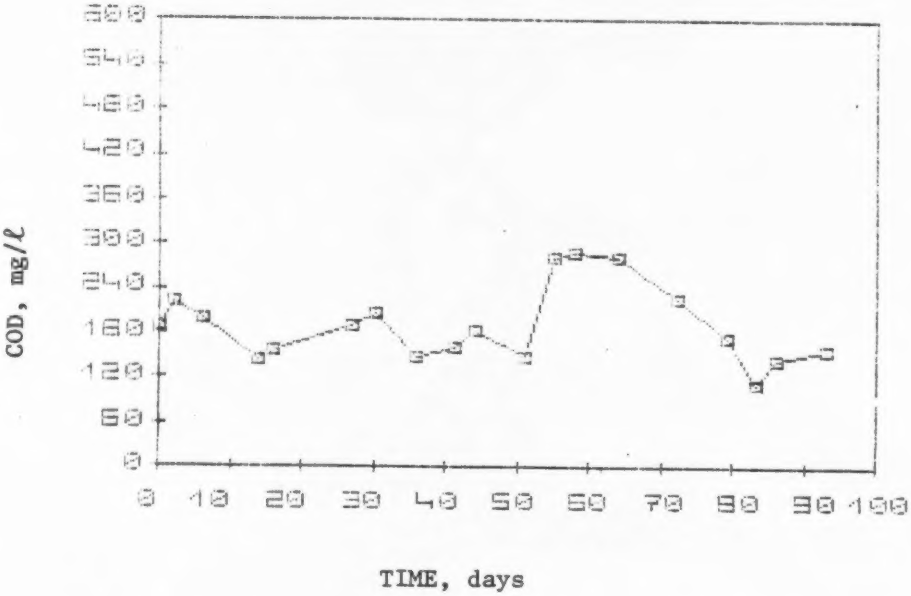


Figure C.4 Chemical oxygen demand concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

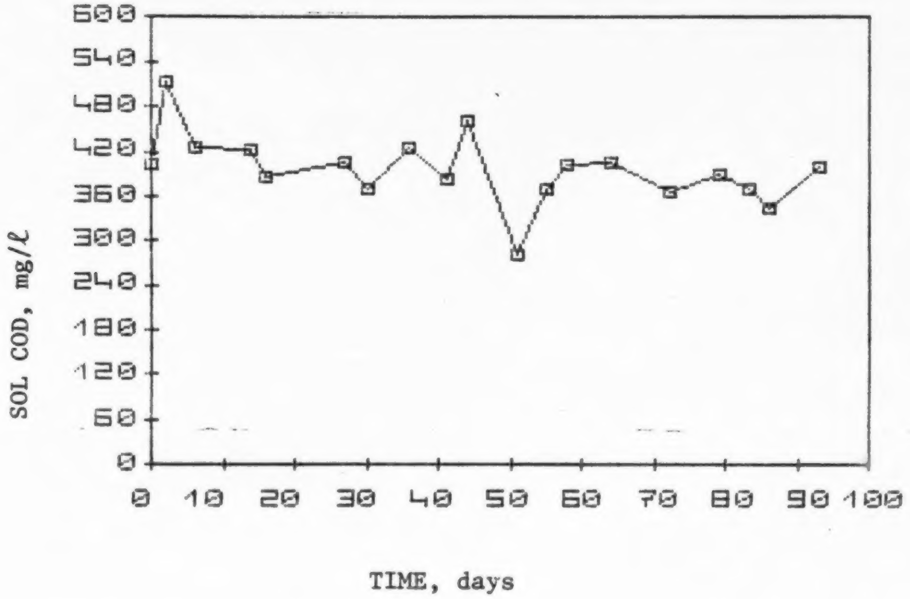


Figure C.5 Soluble oxygen demand concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

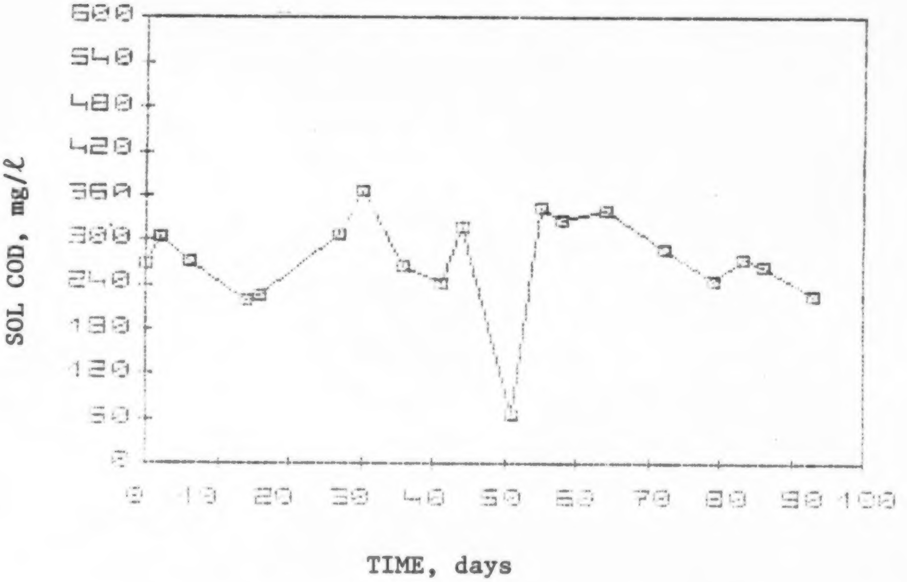


Figure C.6 Soluble oxygen demand concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

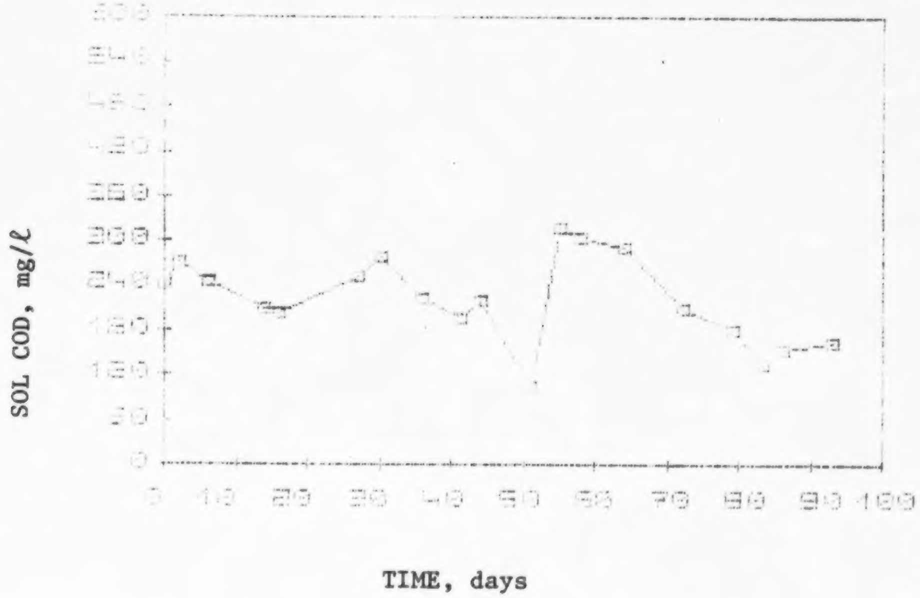


Figure C.7 Soluble oxygen demand concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

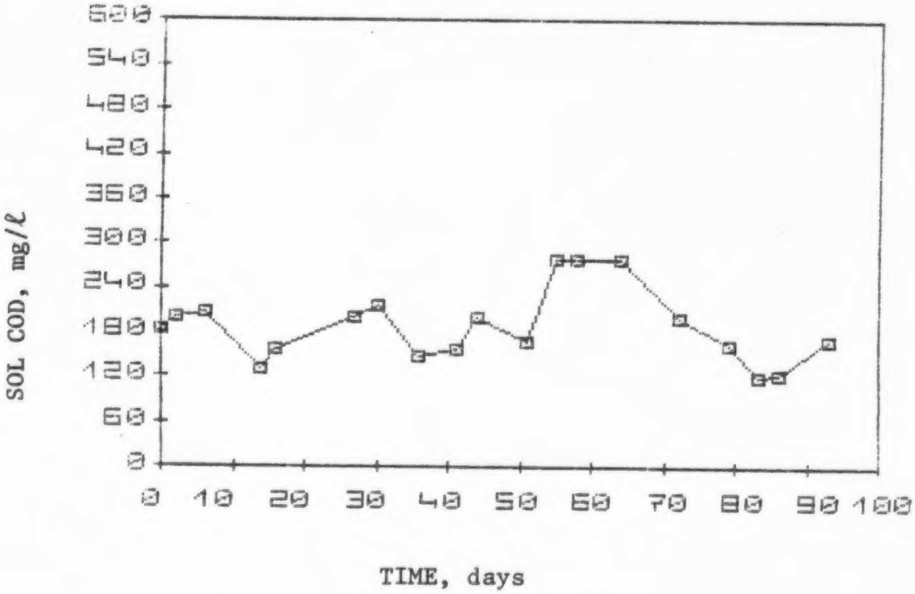


Figure C.8 Soluble oxygen demand concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

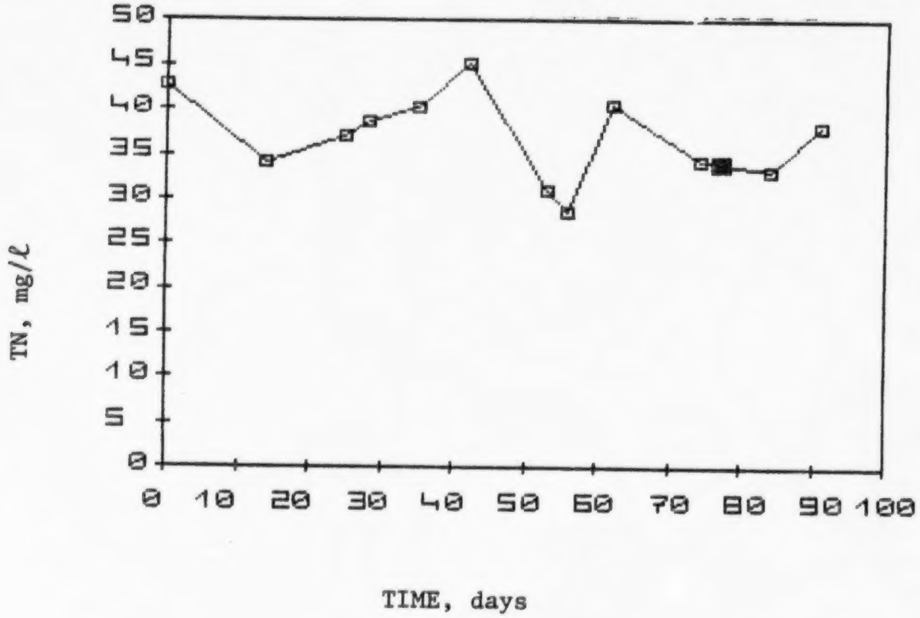


Figure C.9 Total nitrogen concentration of synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

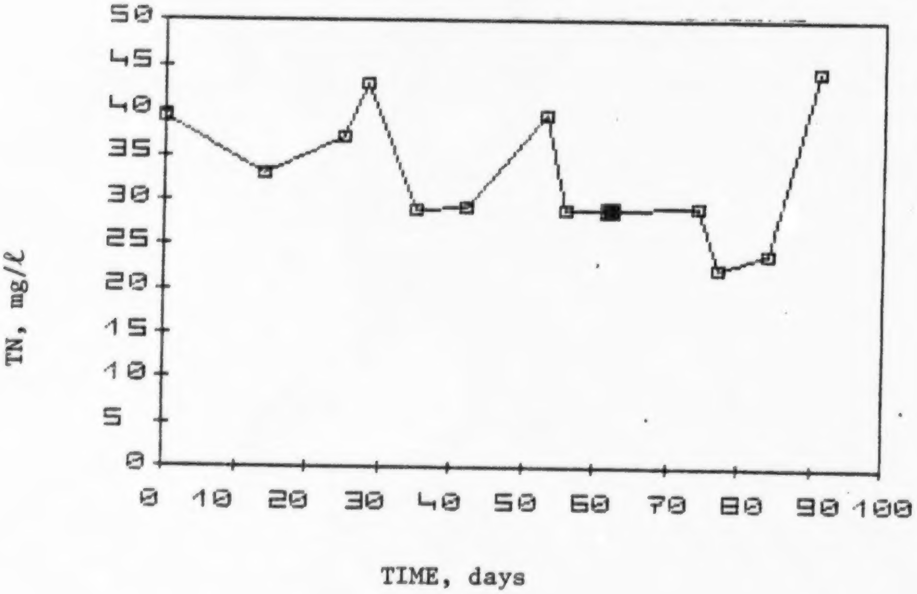


Figure C.10 Total nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

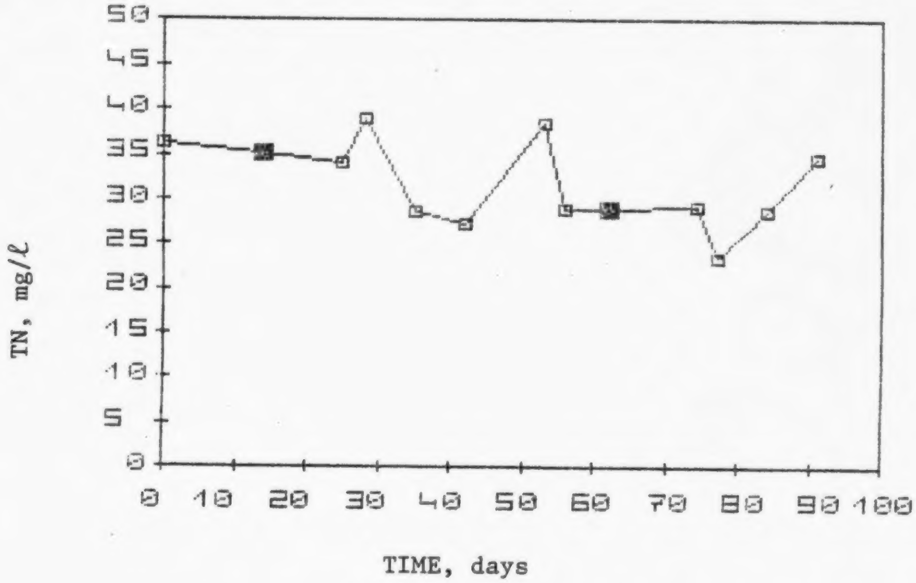


Figure C.11 Total nitrogen concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

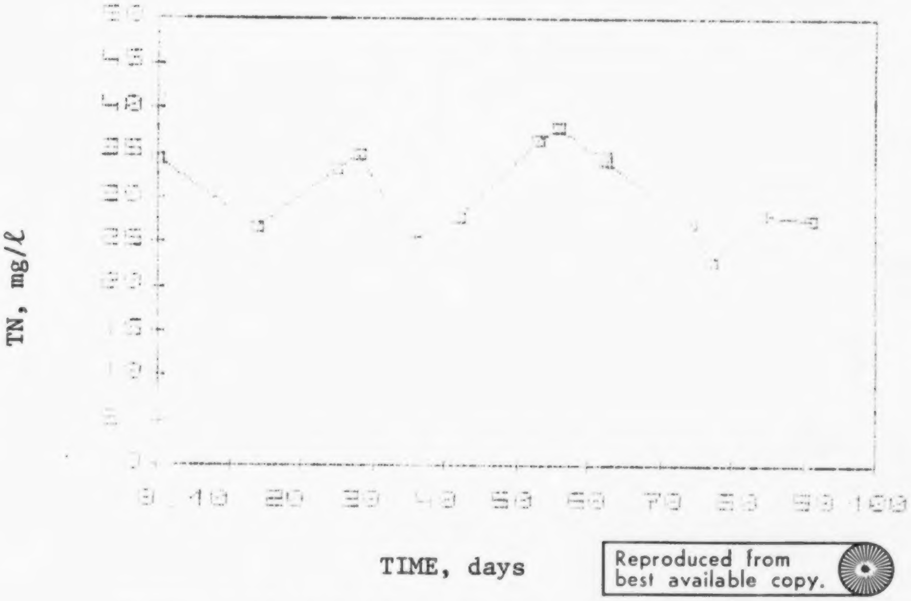


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Figure C.12 Total nitrogen concentration of effluent synthetic sewage from Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

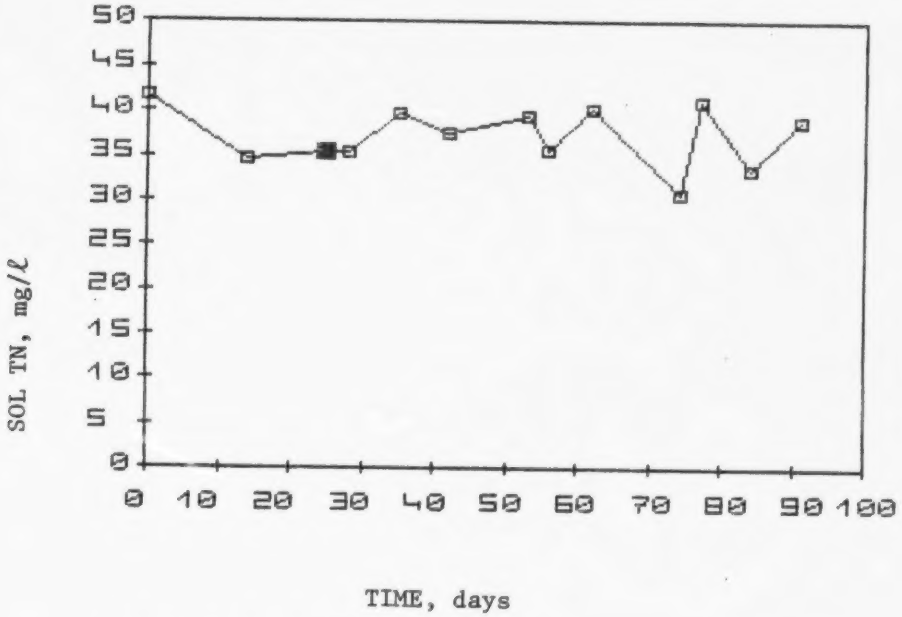


Figure C.13 Soluble total nitrogenconcentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

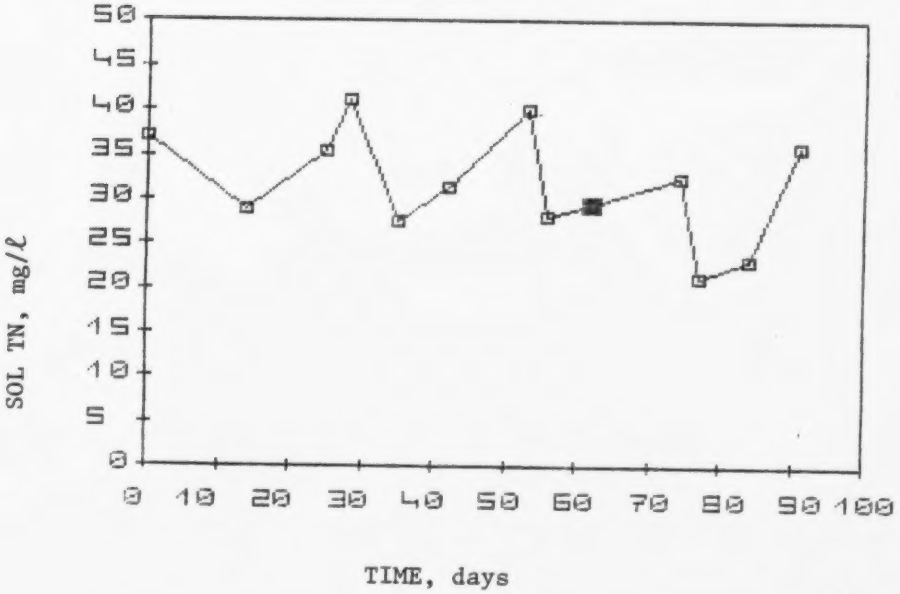
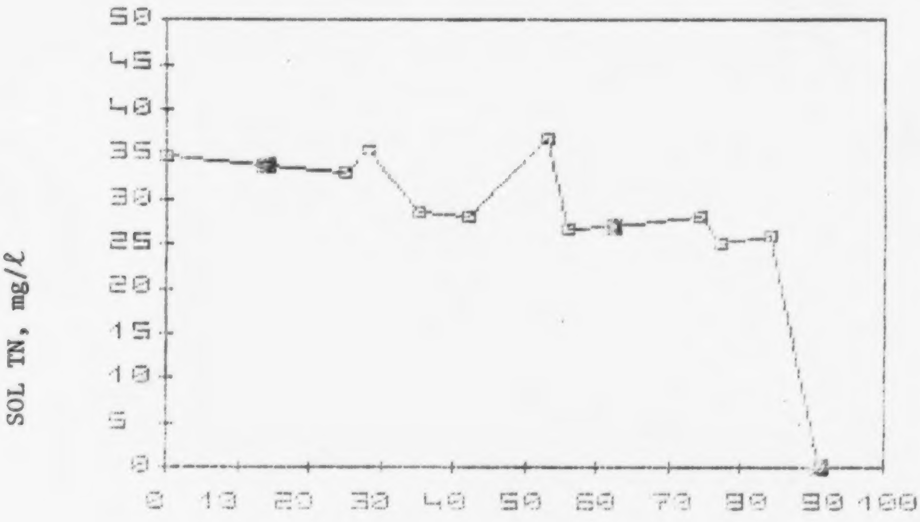
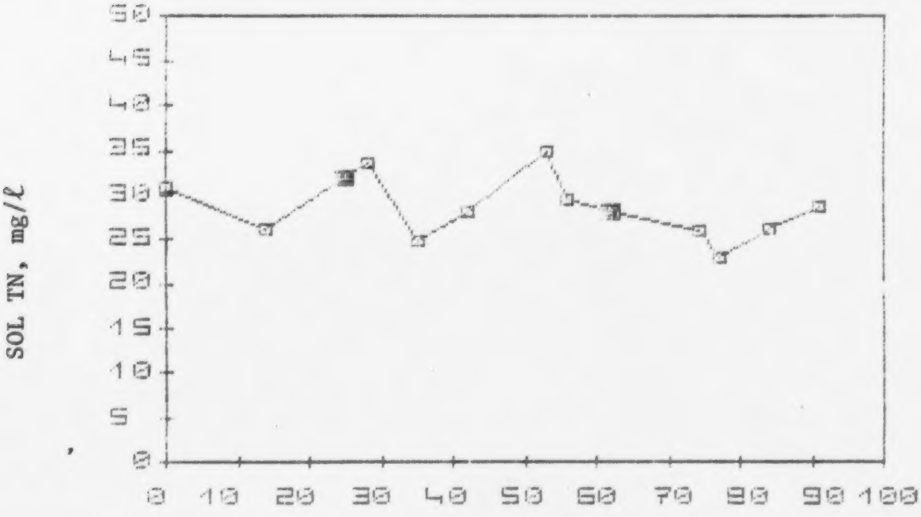


Figure C.14 Soluble total nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.



TIME, days

Figure C.15 Soluble total nitrogen concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.



TIME, days

Figure C.16 Soluble total nitrogen concentration of effluent synthetic sewage from Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

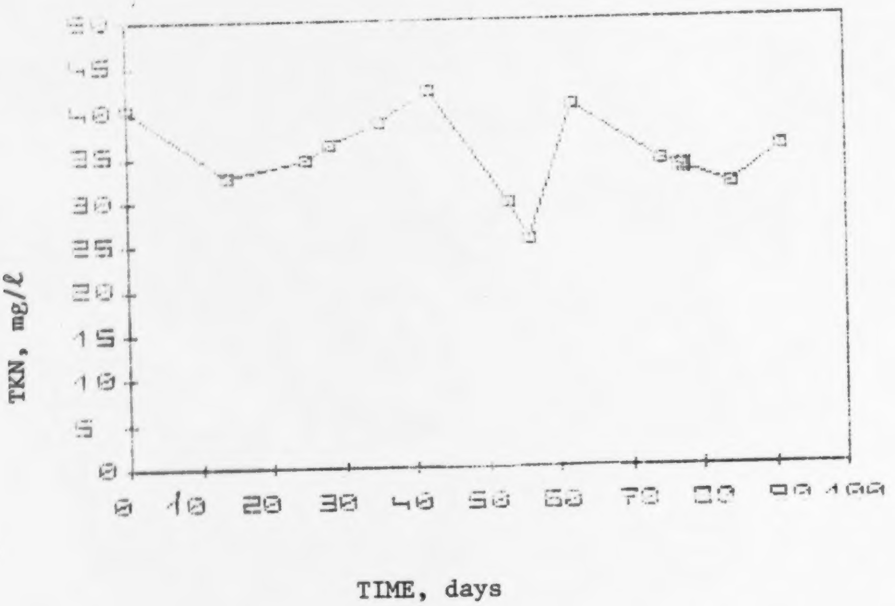


Figure C.17 Total Kjeldahl Nitrogen concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

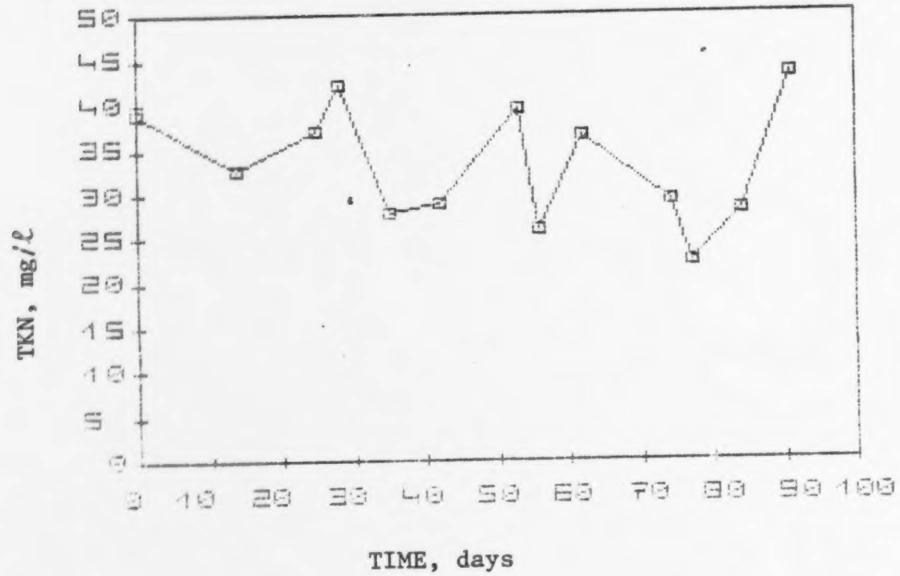


Figure C.18 Total Kjeldahl nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

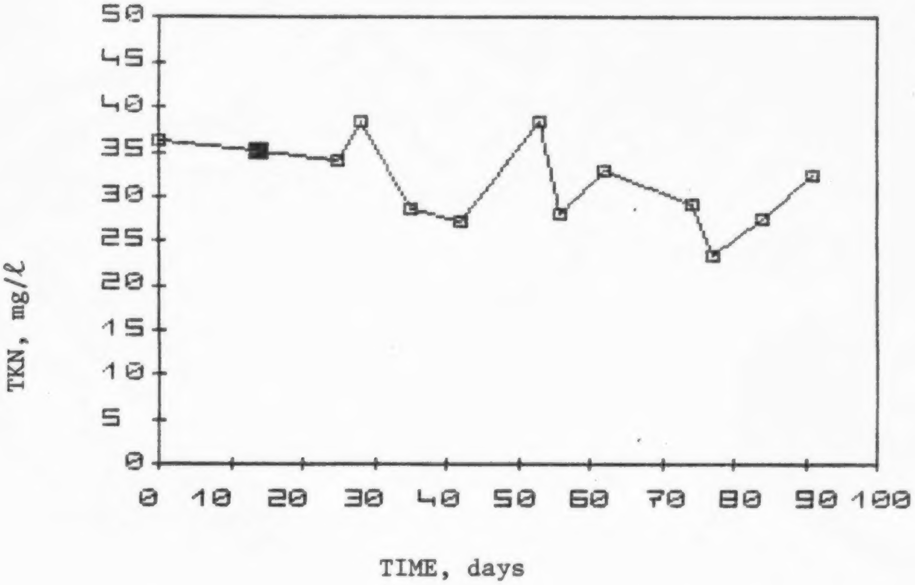


Figure C.19 Total Kjeldahl Nitrogen concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

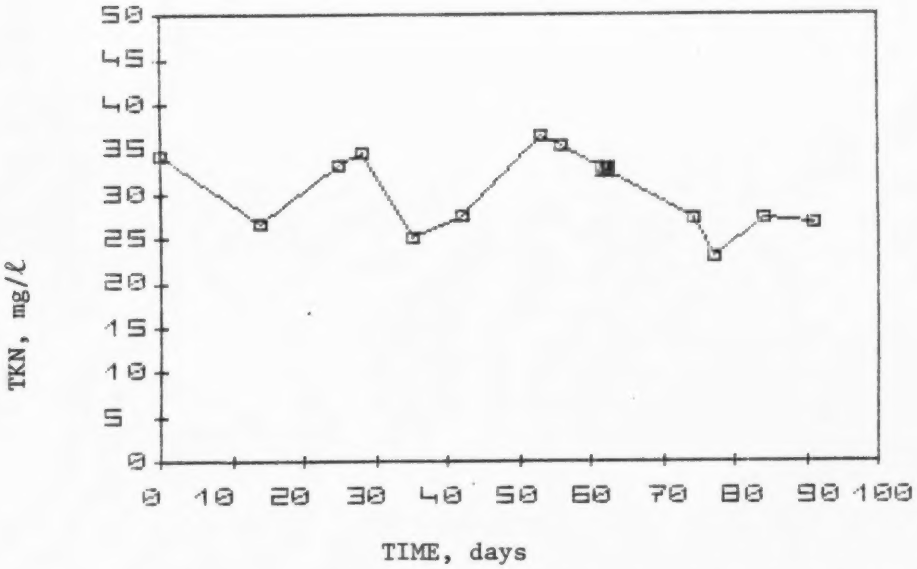


Figure C.20 Total Kjeldahl Nitrogen concentration of effluent synthetic sewage from Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

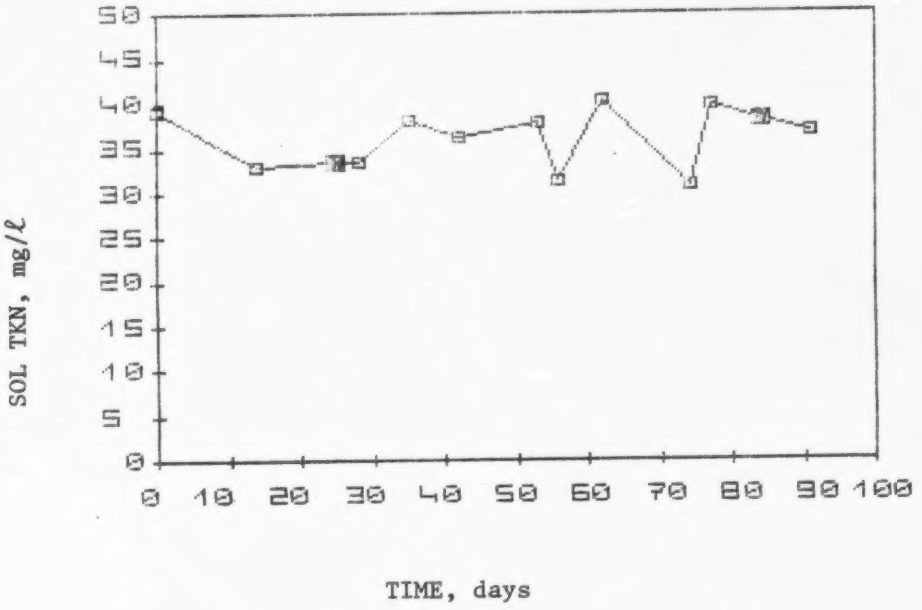


Figure C.21 Soluble total Kjeldahl nitrogen concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

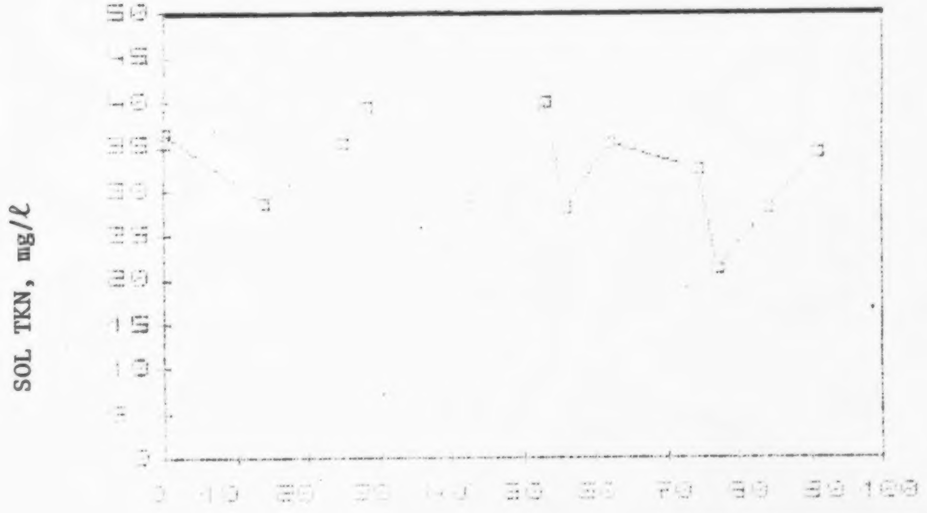


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Figure C.22 Soluble total Kjeldahl nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

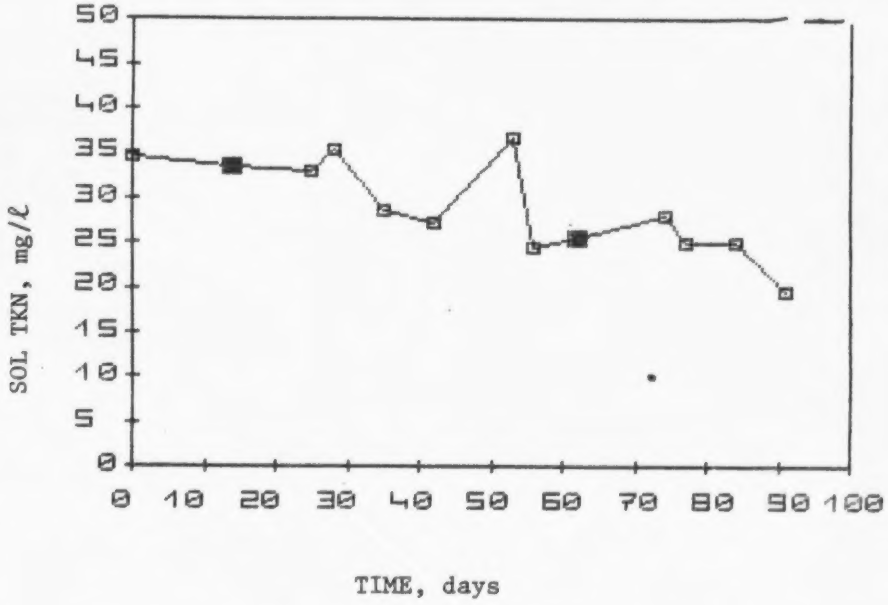


Figure C.23 Soluble total Kjeldahl nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

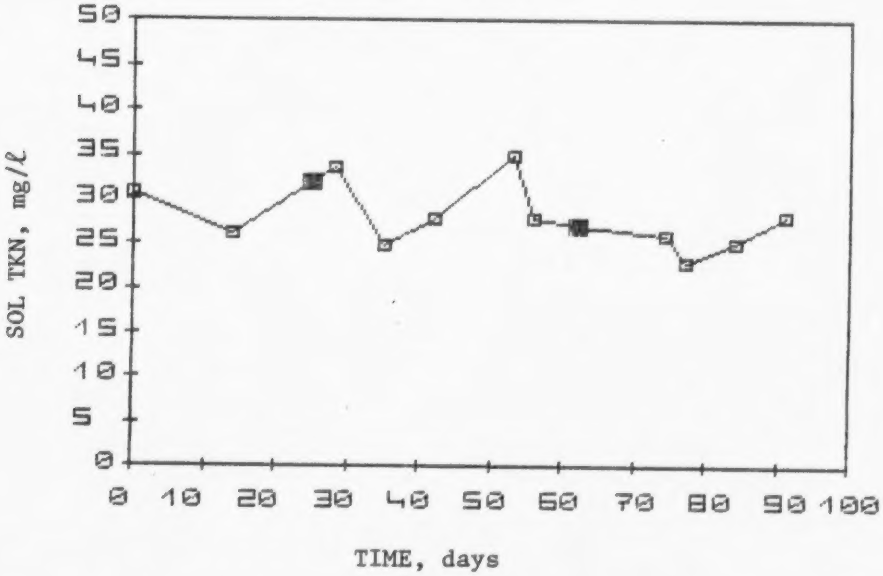


Figure C.24 Soluble total Kjeldahl nitrogen concentration of effluent synthetic sewage from Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

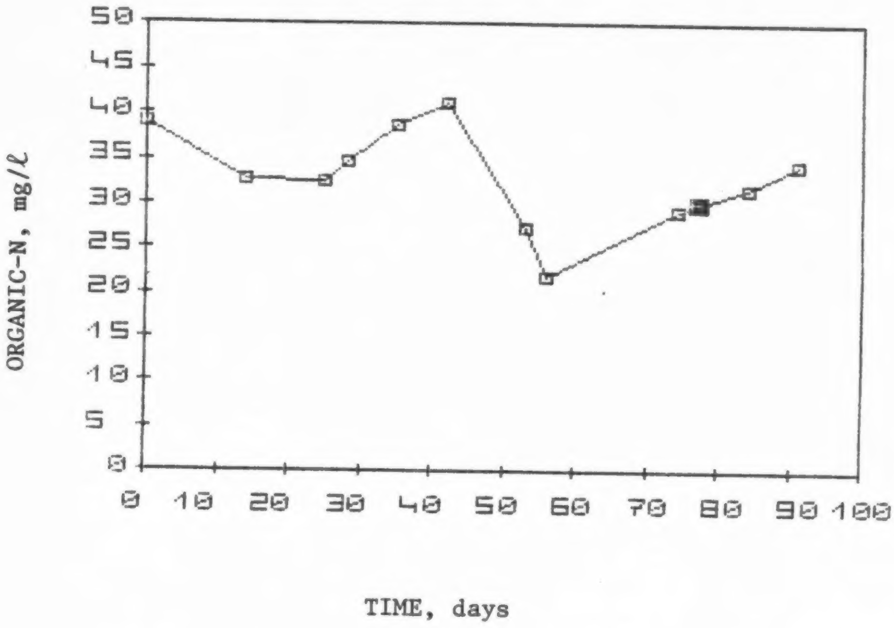


Figure C.25 Organic nitrogen concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

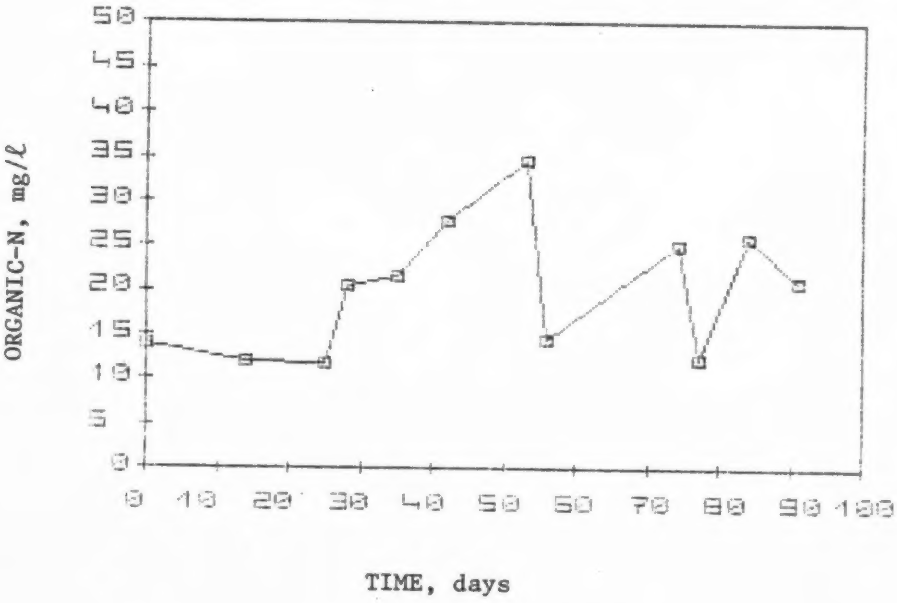


Figure C.26 Organic nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

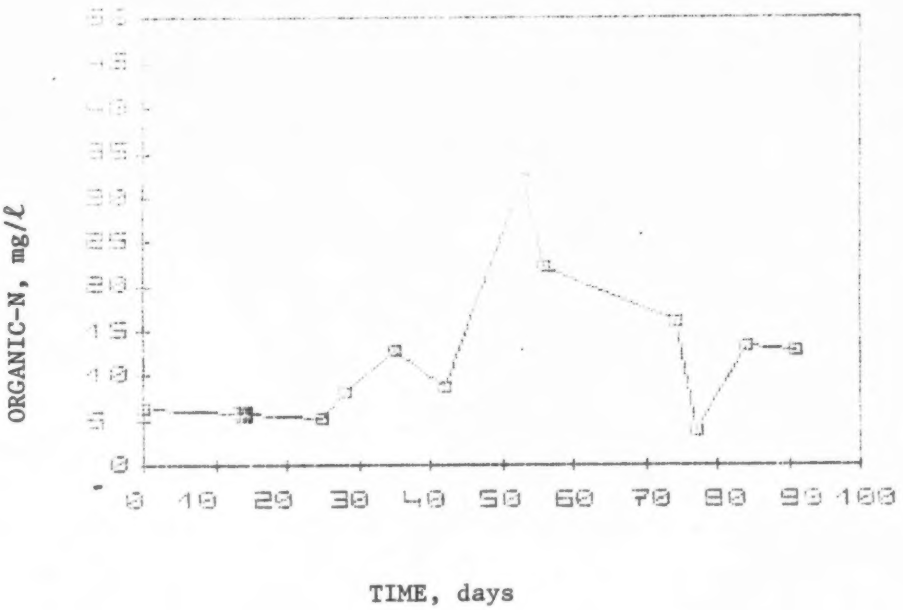


Figure C.27 Organic nitrogen concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

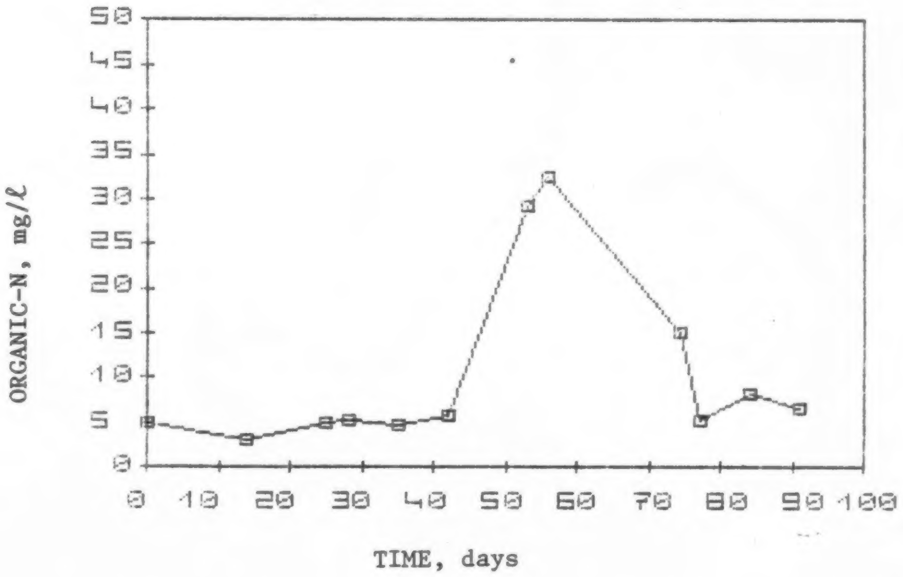


Figure C.28 Organic nitrogen concentration of effluent synthetic sewage from Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

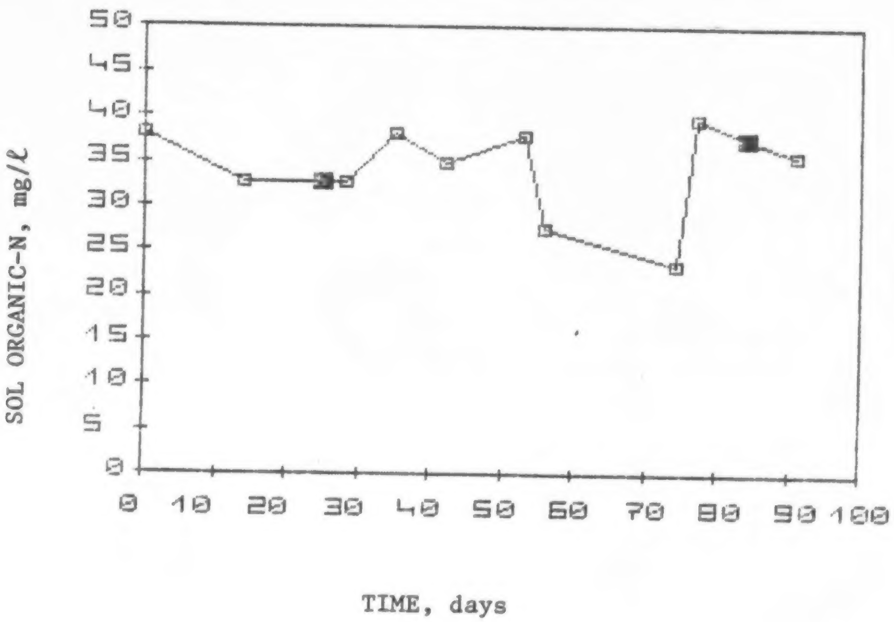


Figure C.29 Soluble organic nitrogen concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

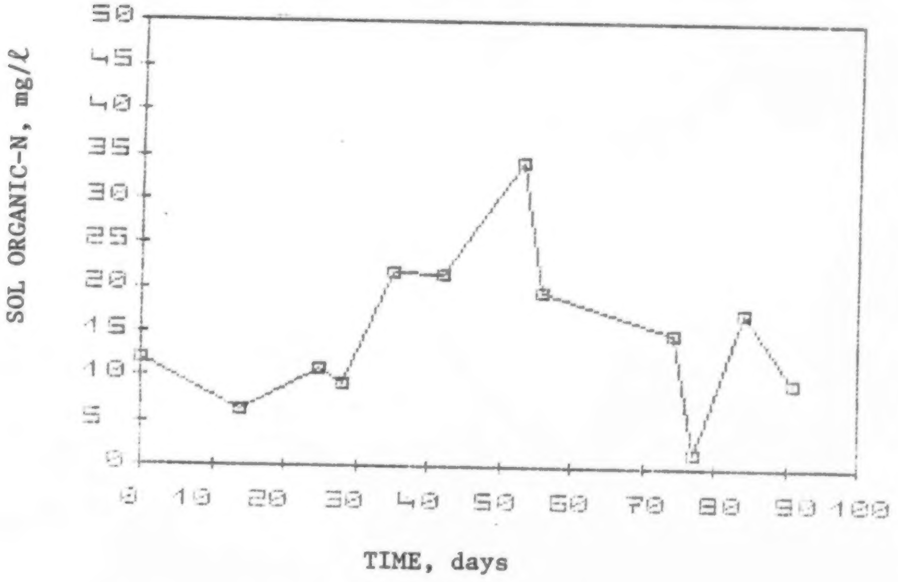


Figure C.30 Soluble organic nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

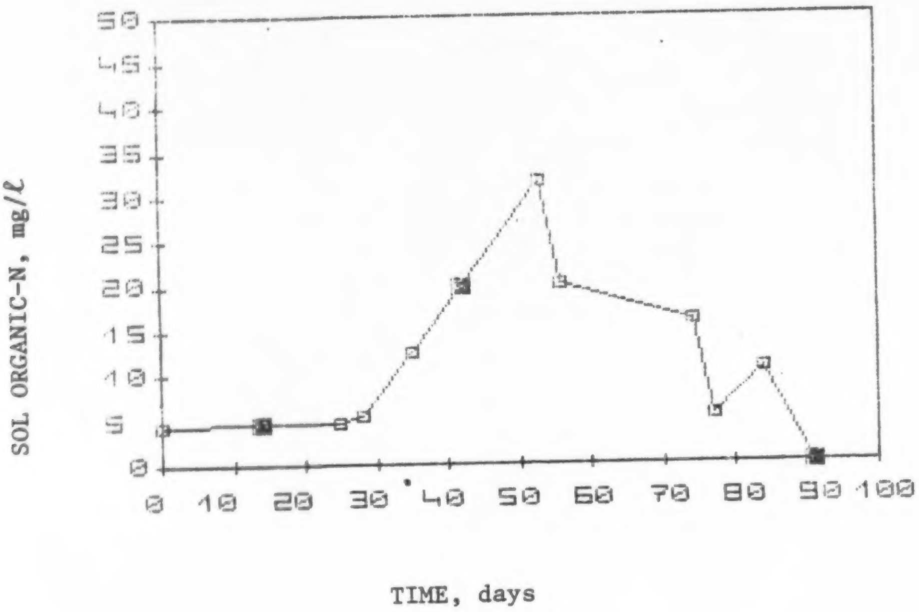


Figure C.31 Soluble organic nitrogen concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

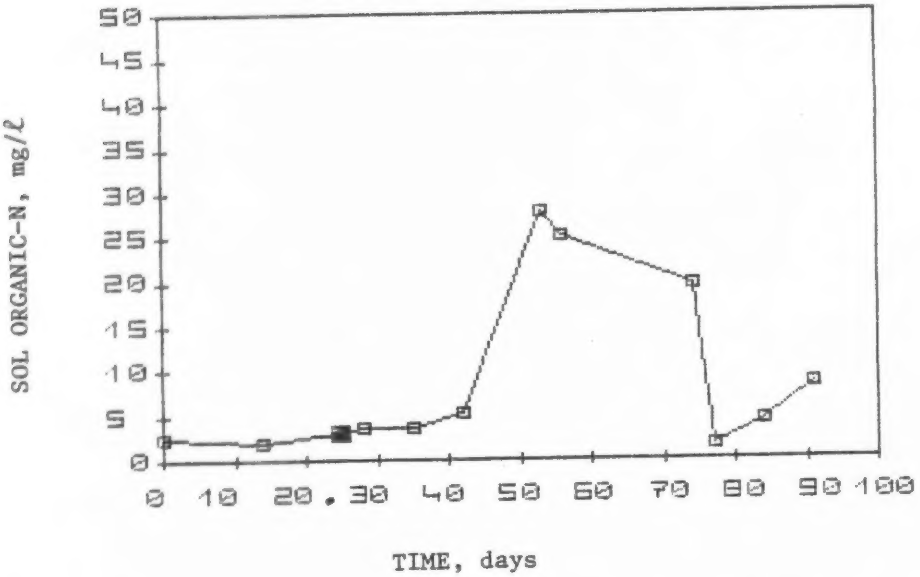


Figure C.32 Soluble organic nitrogen concentration of effluent synthetic sewage from Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

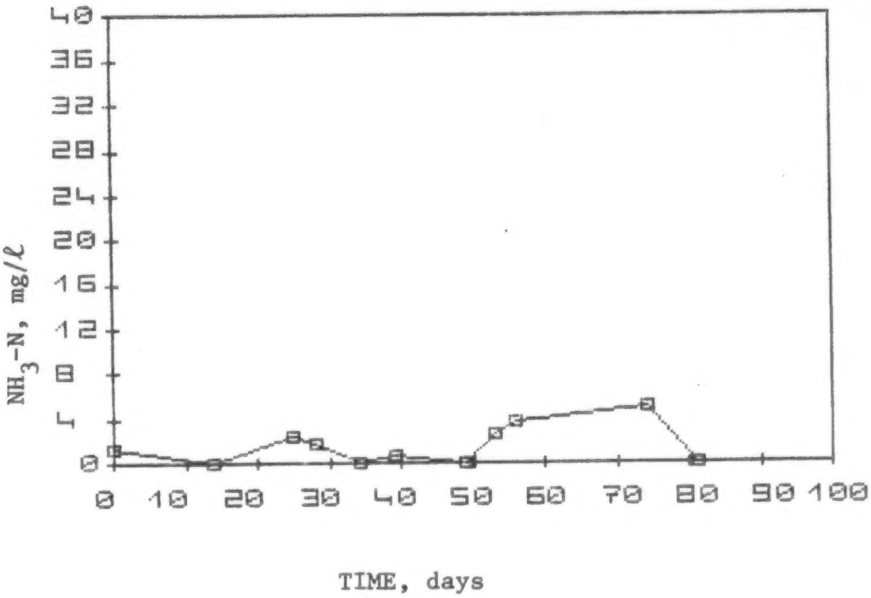


Figure C.33 Ammonia nitrogen concentration of influent synthetic sewage to the Cornell NFT in Phase O. First day of analysis was December 7, 1979.

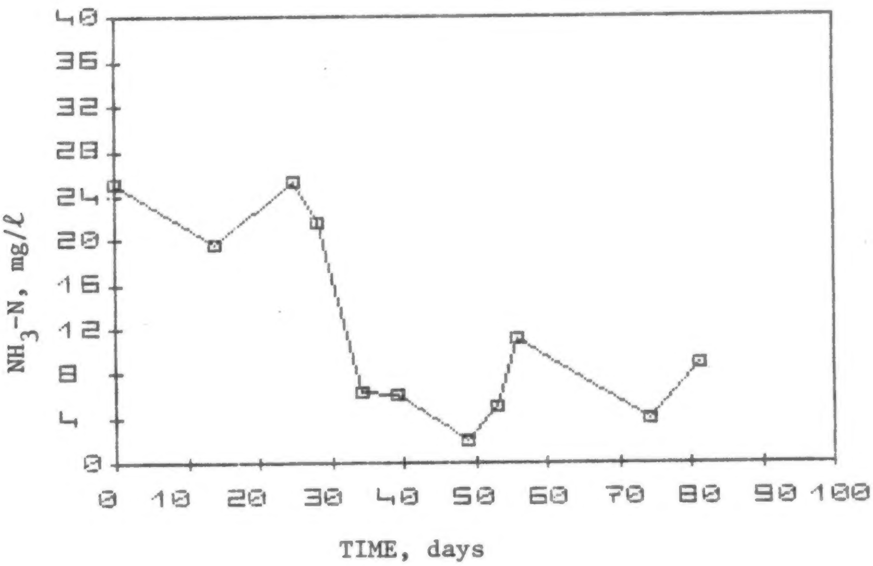
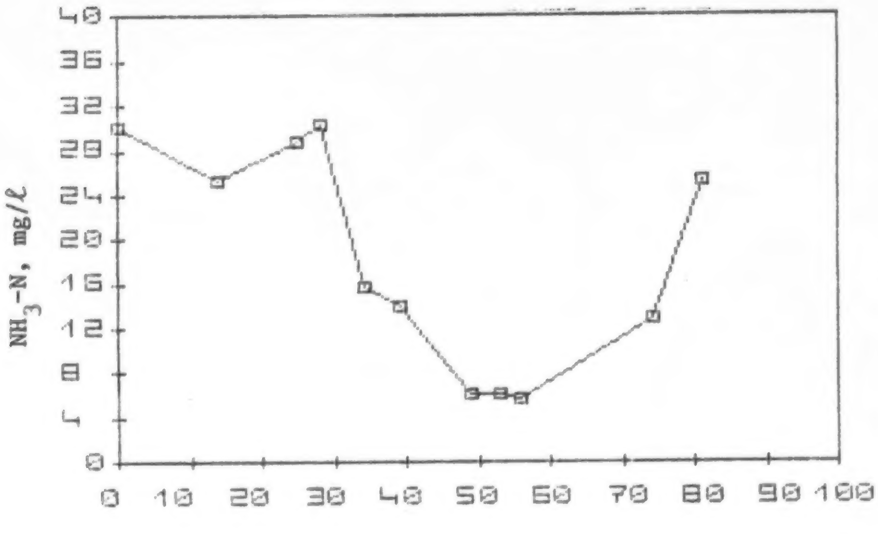
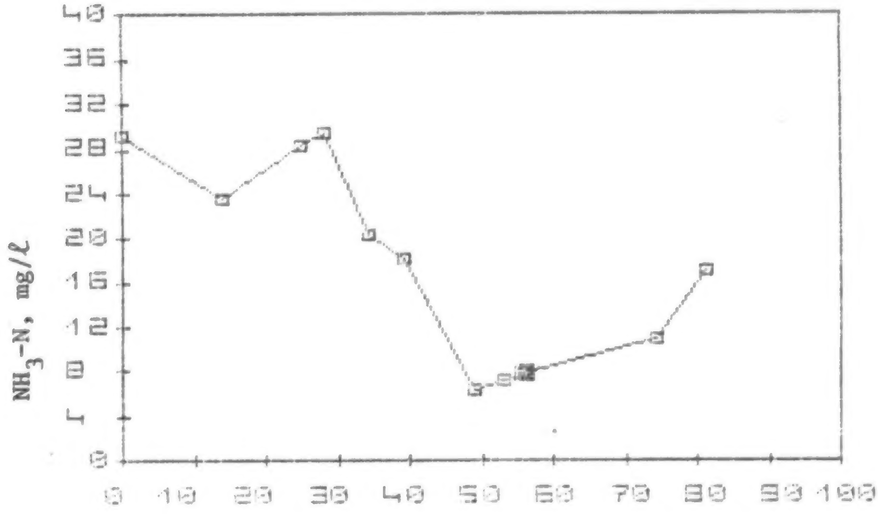


Figure C.34 Ammonia nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase O. First day of analysis was December 7, 1979.



TIME, days

Figure C.35 Ammonia nitrogen concentration of synthetic sewage at Point B in the Cornell NFT in Phase O. First day of analysis was December 7, 1979.



TIME, days

Figure C.36 Ammonia nitrogen concentration of effluent synthetic sewage from Cornell NFT in Phase O. First day of analysis was December 7, 1979.

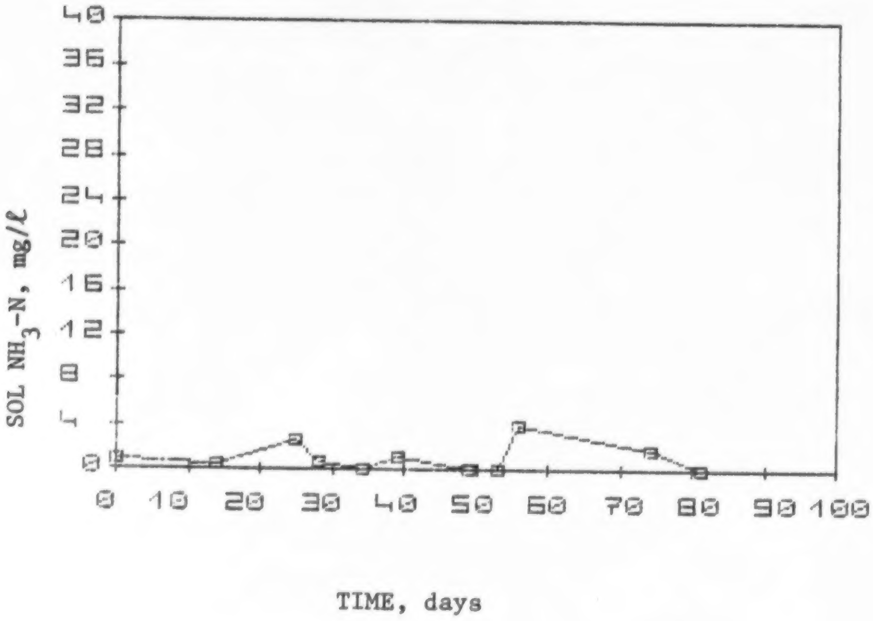


Figure C.37 Soluble ammonia nitrogen concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

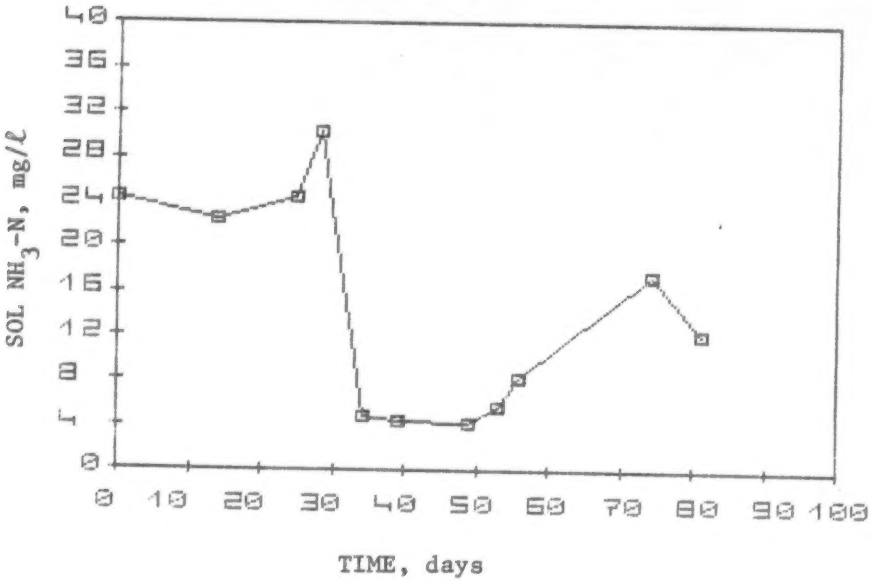


Figure C.38 Soluble ammonia nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

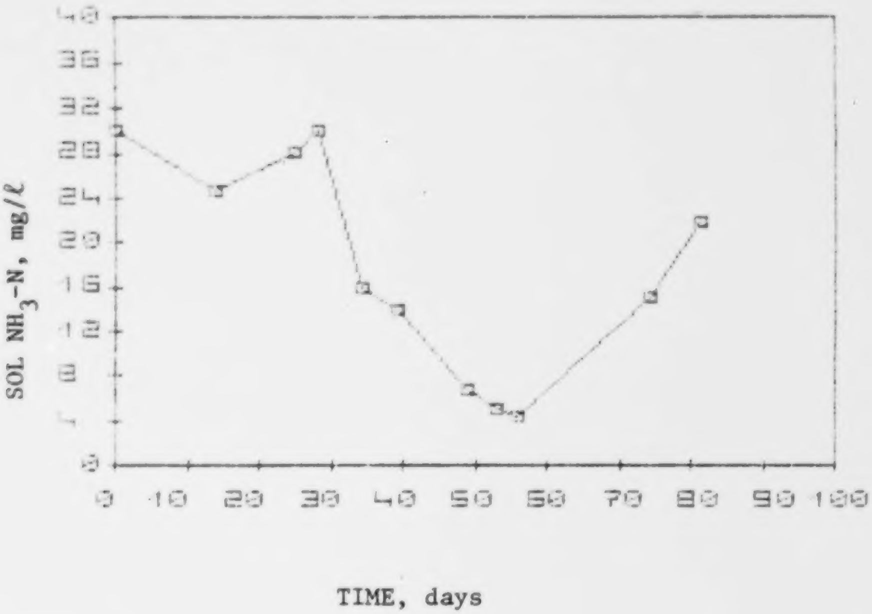


Figure C.39 Soluble ammonia nitrogen concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

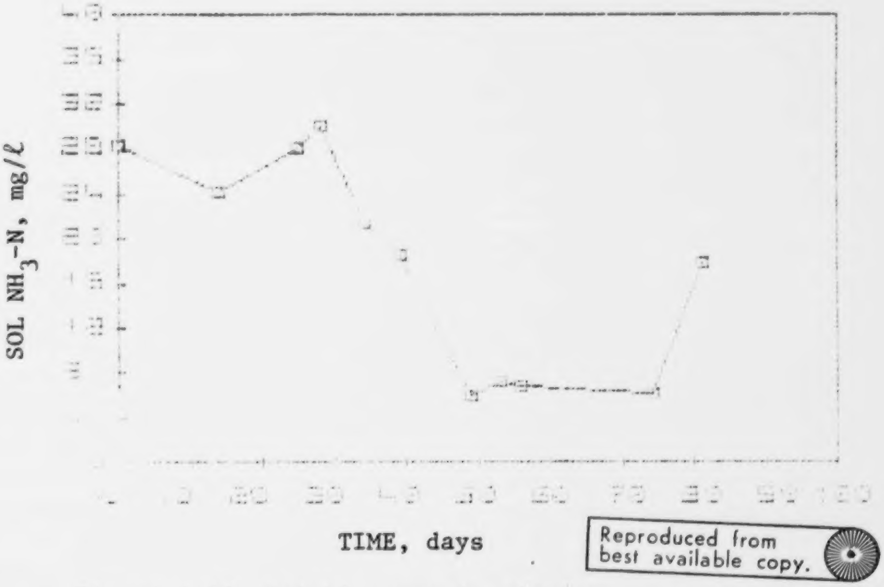


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Figure C.40 Soluble ammonia nitrogen concentration of effluent synthetic sewage from Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

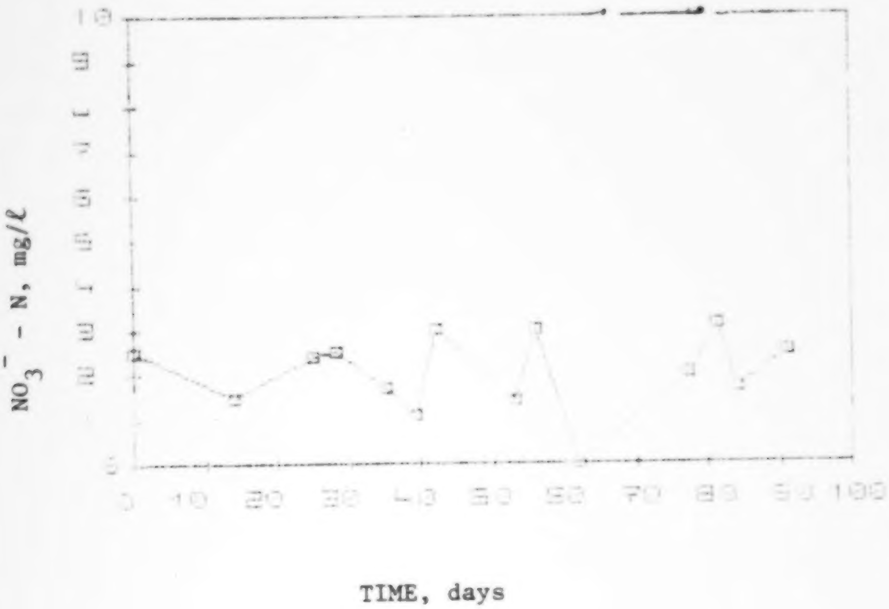

Figure C.41 Nitrate nitrogen concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

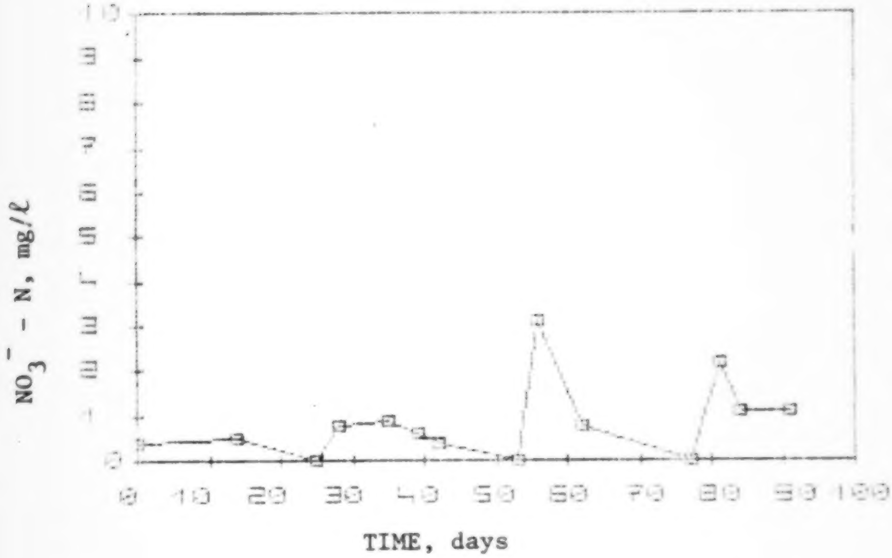

Figure C.42 Nitrate nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

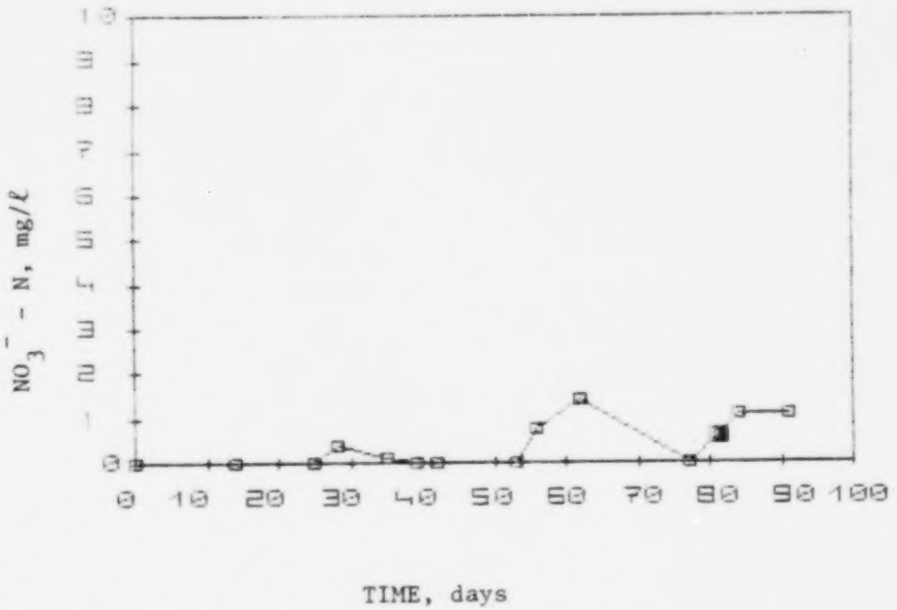

Figure C.43 Nitrate nitrogen concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

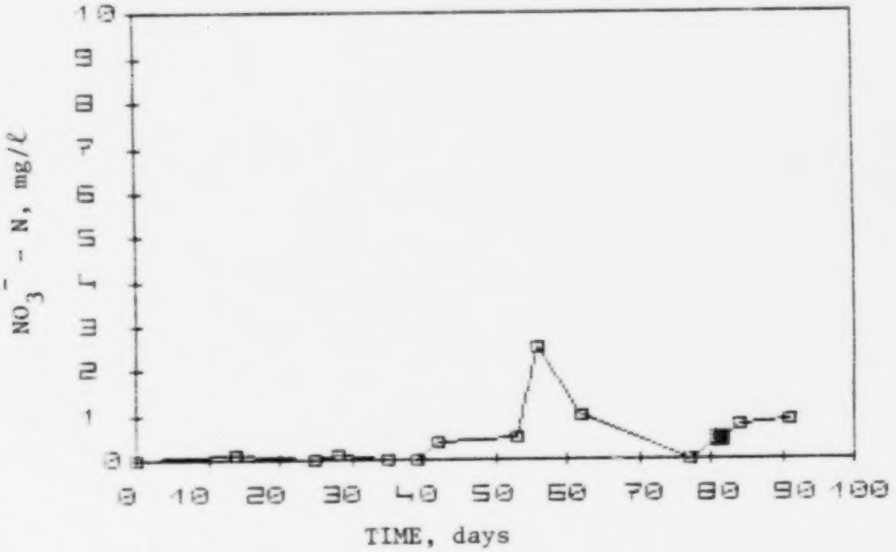

Figure C.44 Nitrate nitrogen concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

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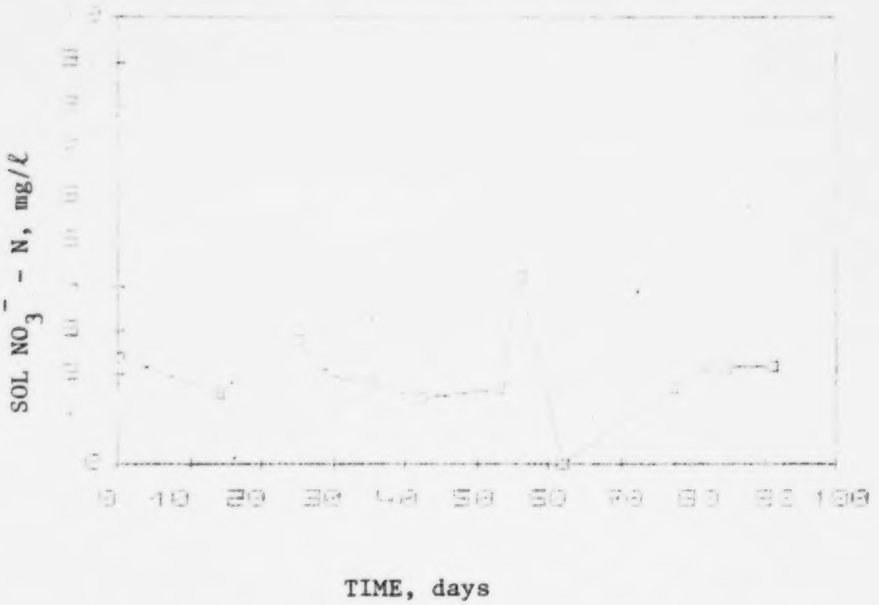


Figure C.45 Soluble nitrate nitrogen concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

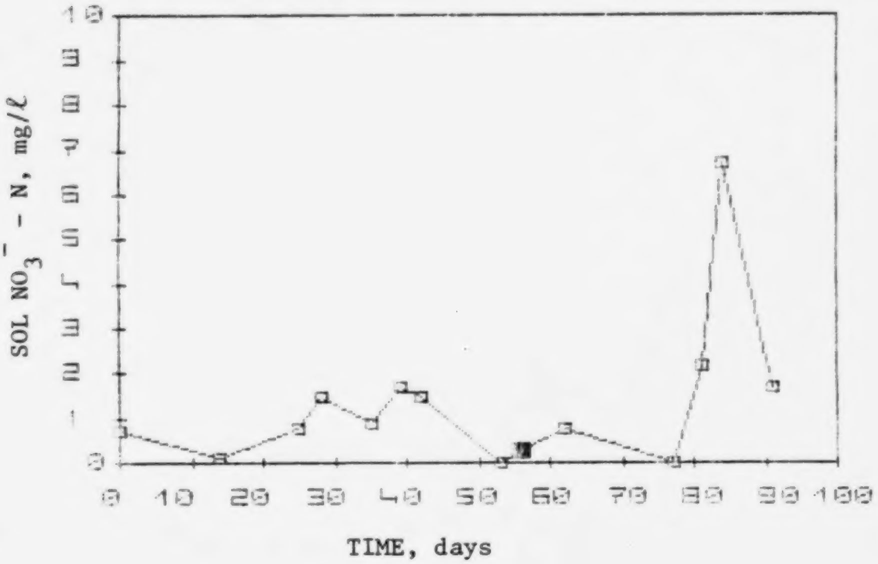


Figure C.46 Soluble nitrate nitrogen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

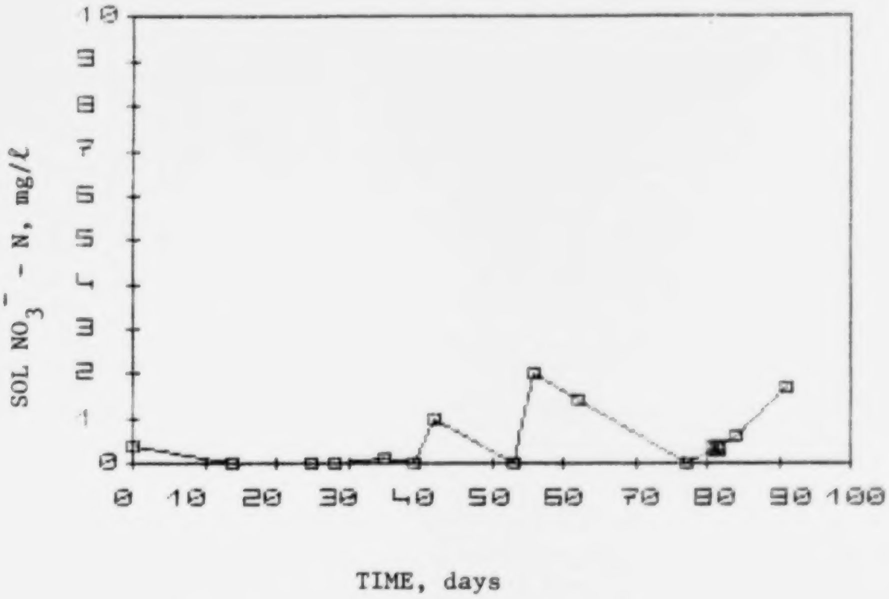


Figure C.47 Soluble nitrate nitrogen concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

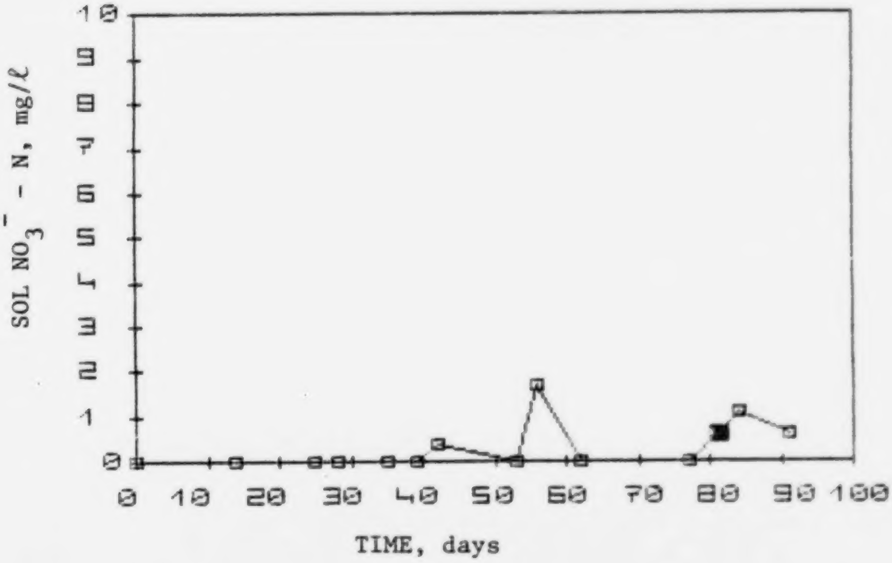


Figure C.48 Soluble nitrate nitrogen concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

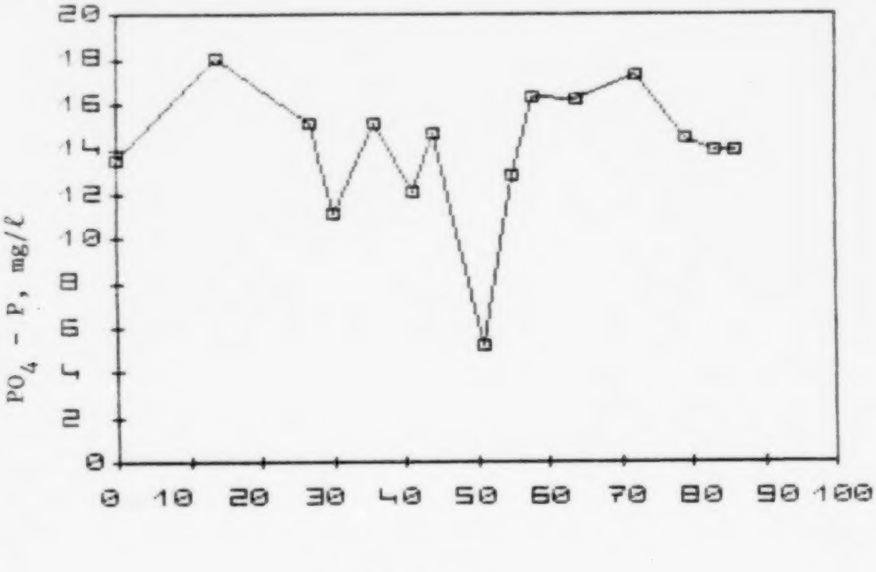


Figure C.49 Orthophosphate concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

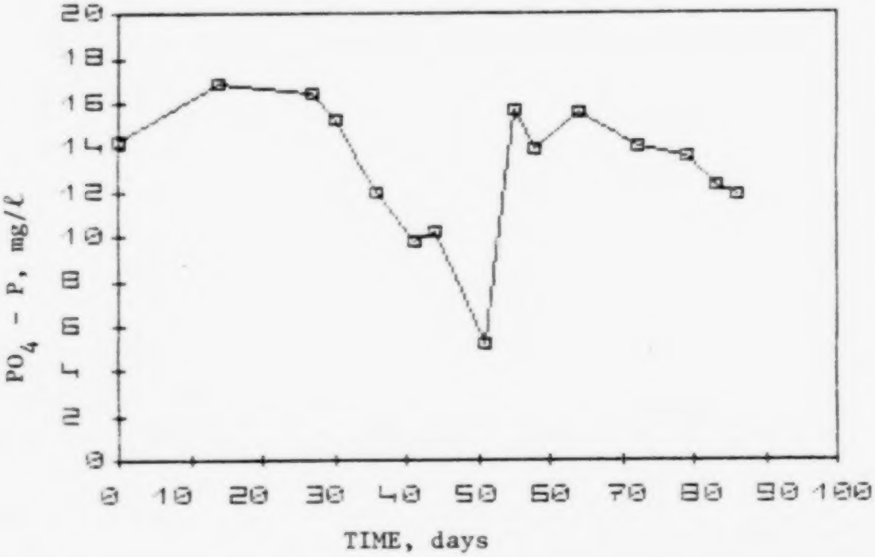


Figure C.50 Orthophosphate concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

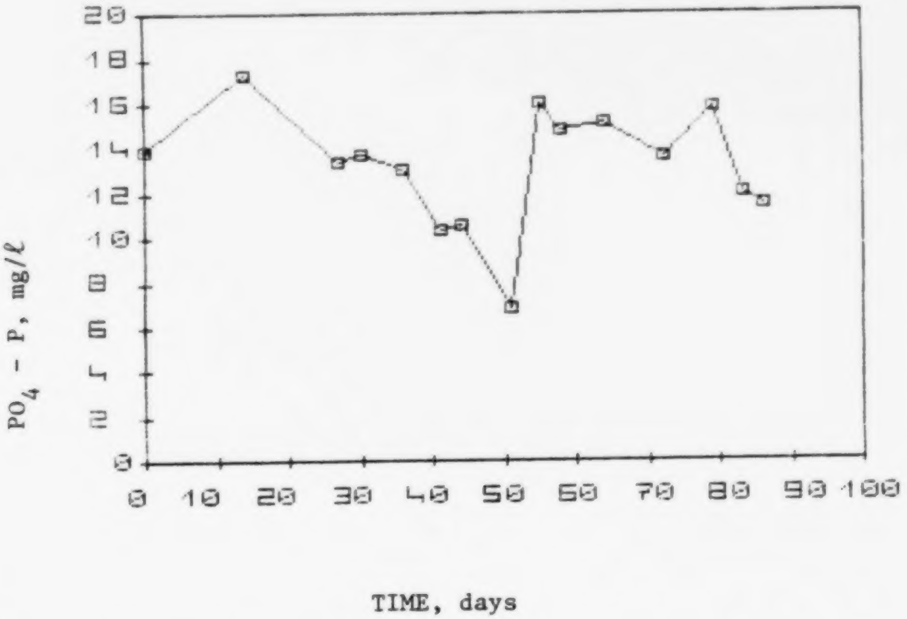


Figure C.51 Orthophosphate concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

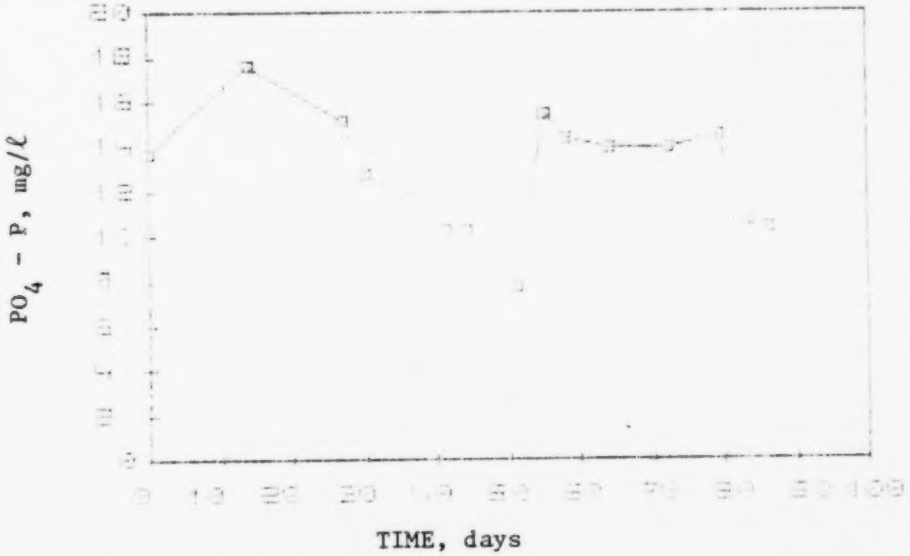


Figure C.52 Orthophosphate concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

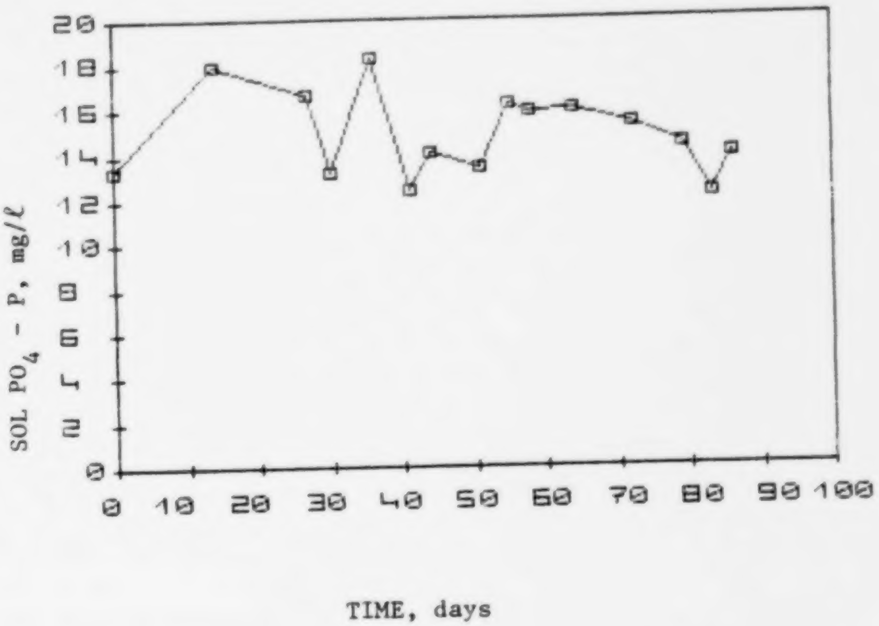


Figure C.53 Soluble orthophosphate concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

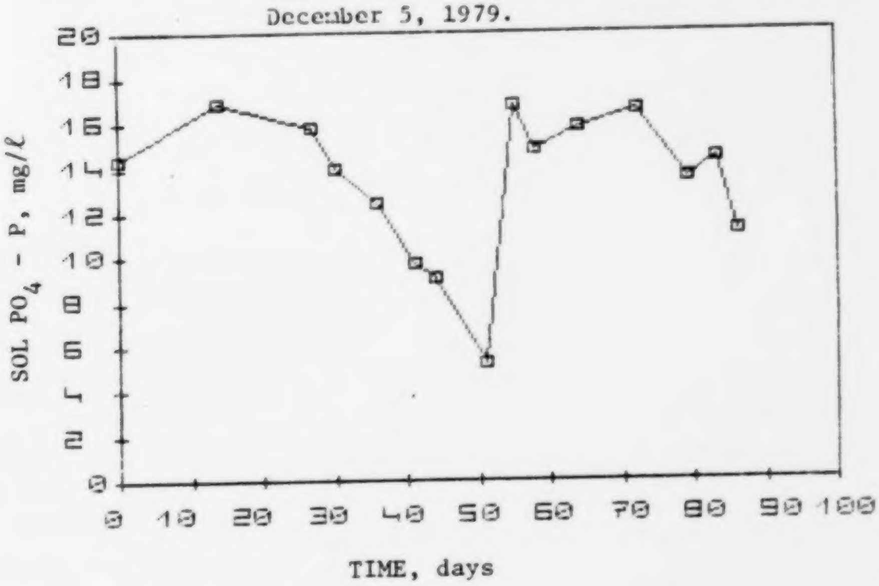


Figure C.54 Soluble orthphosphate concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

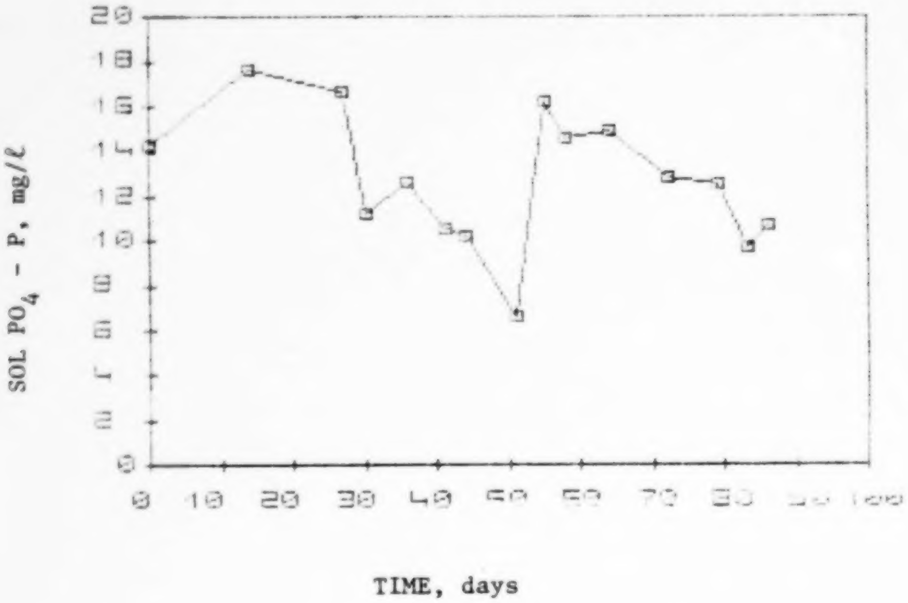


Figure C.55 Soluble orthophosphate concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

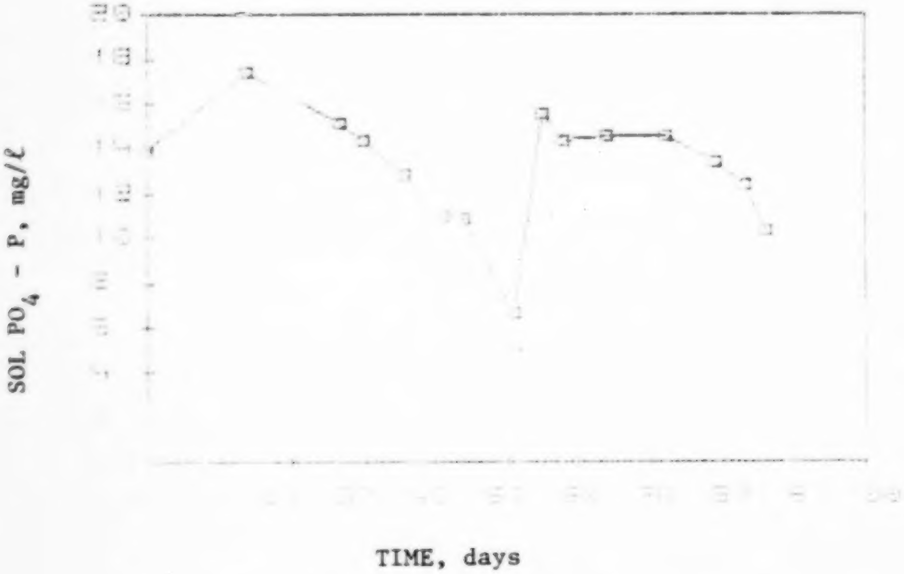


Figure C.56 Soluble orthophosphate concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

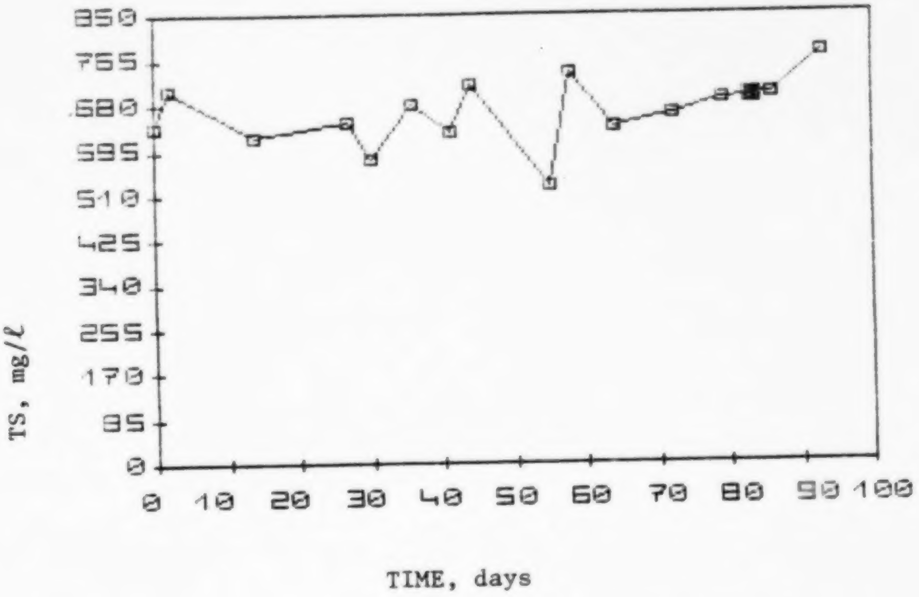


Figure C.57 Total solids concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

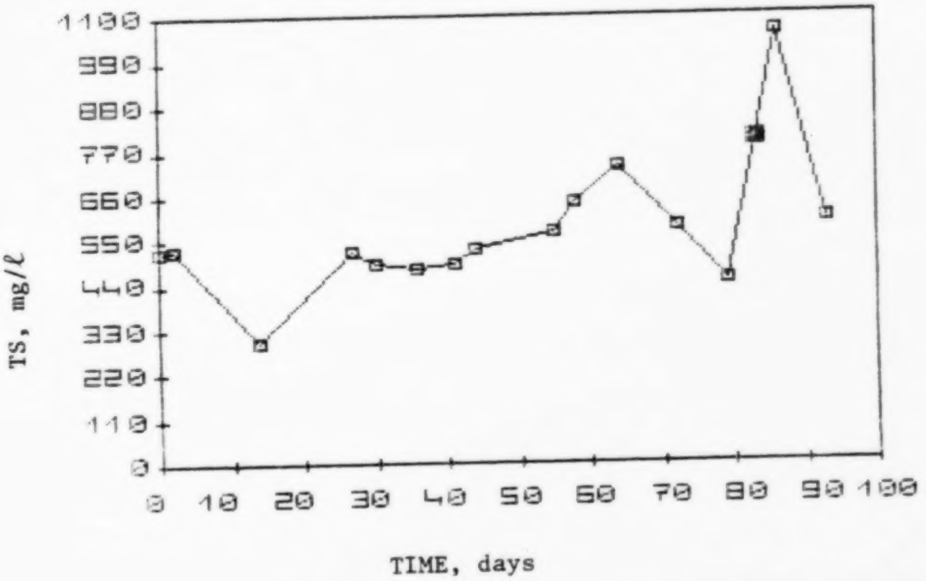


Figure C.58 Total solids concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

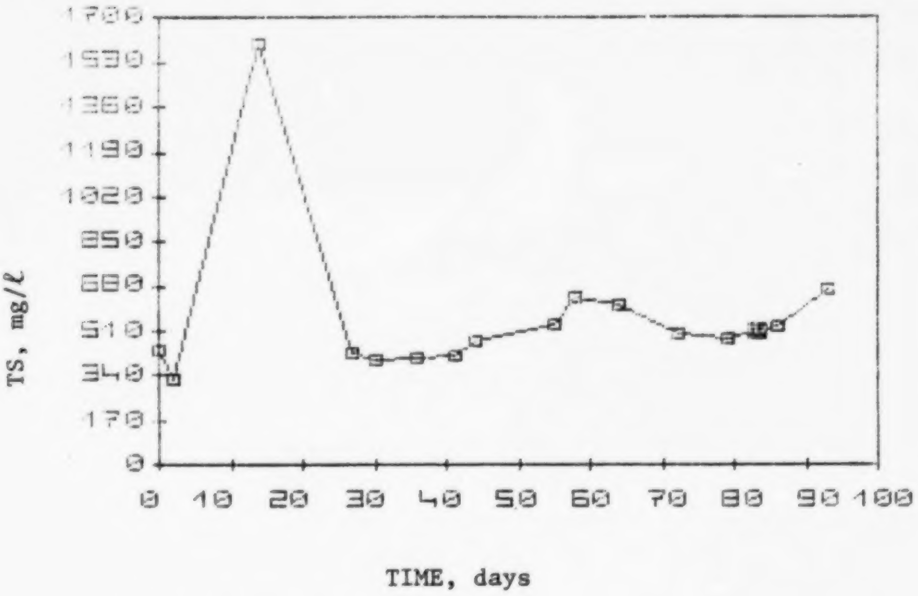


Figure C.59 Total solids concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

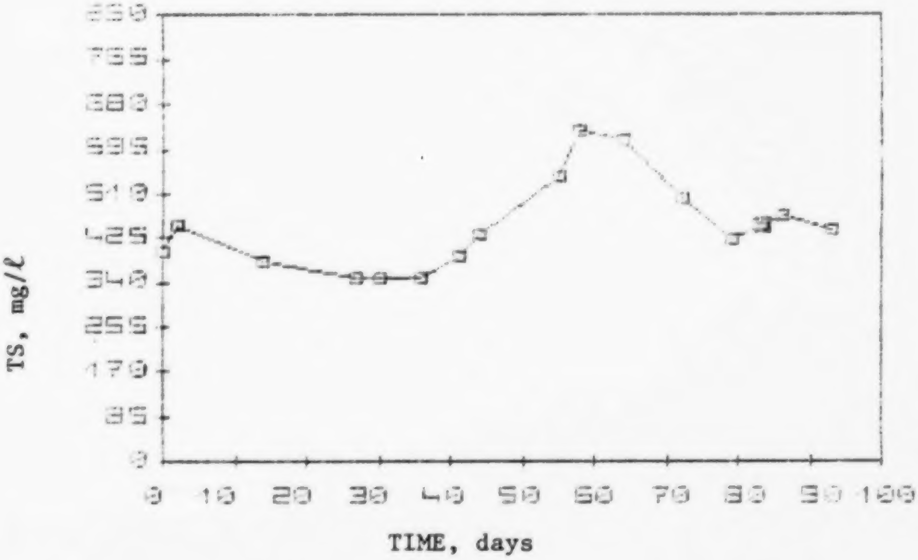


Figure C.60 Total solids concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

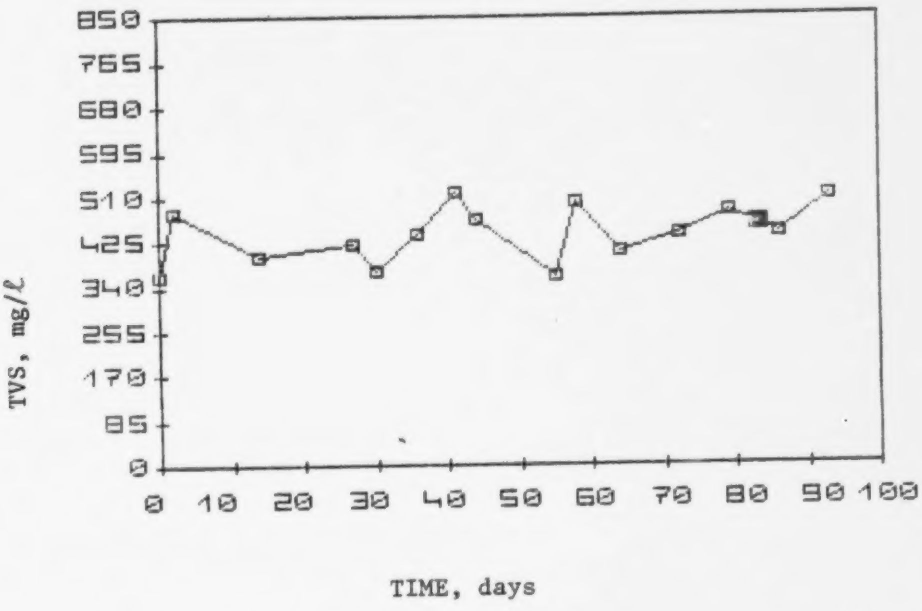


Figure C.61 Total volatile solids concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

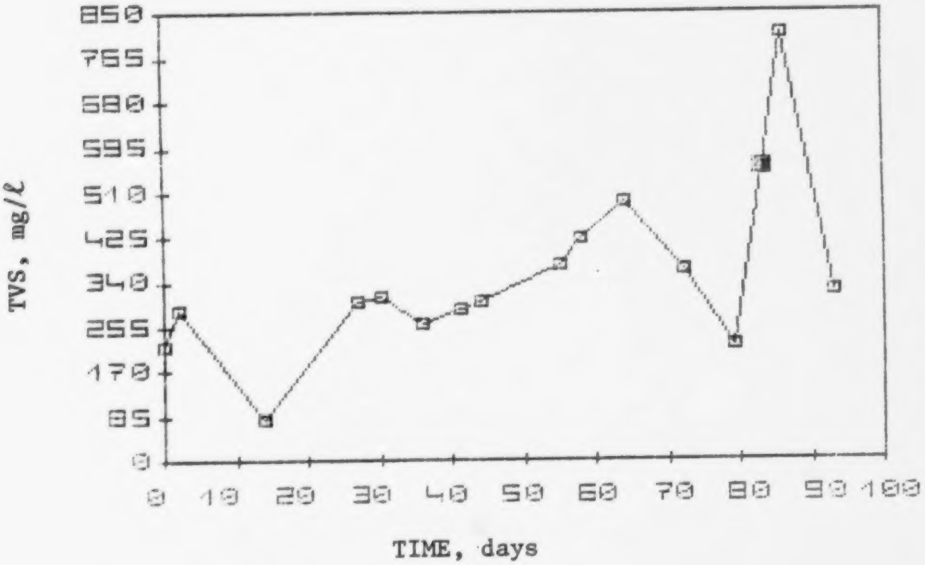


Figure C.62 Total volatile solids concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

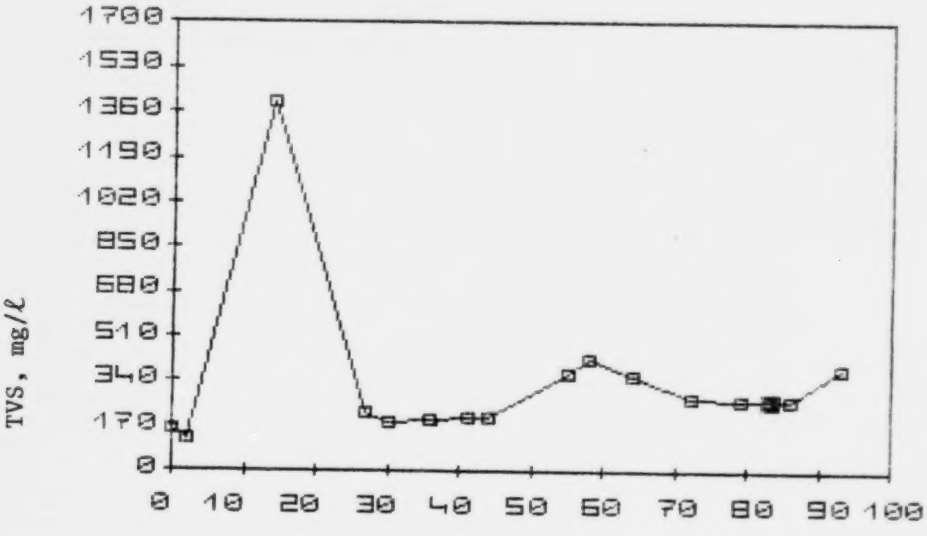


Figure C.63 Total volatile solids concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

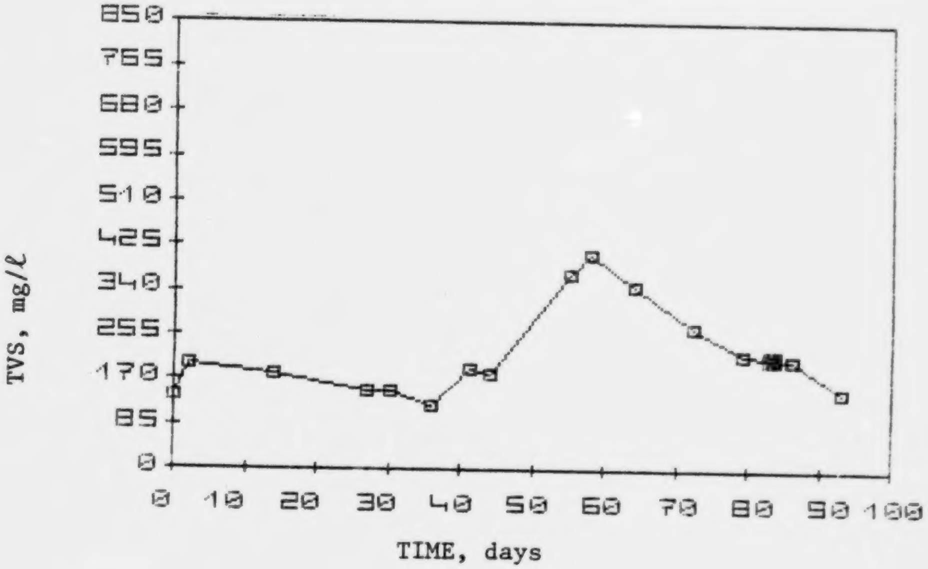


Figure C.64 Total volatile solids concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

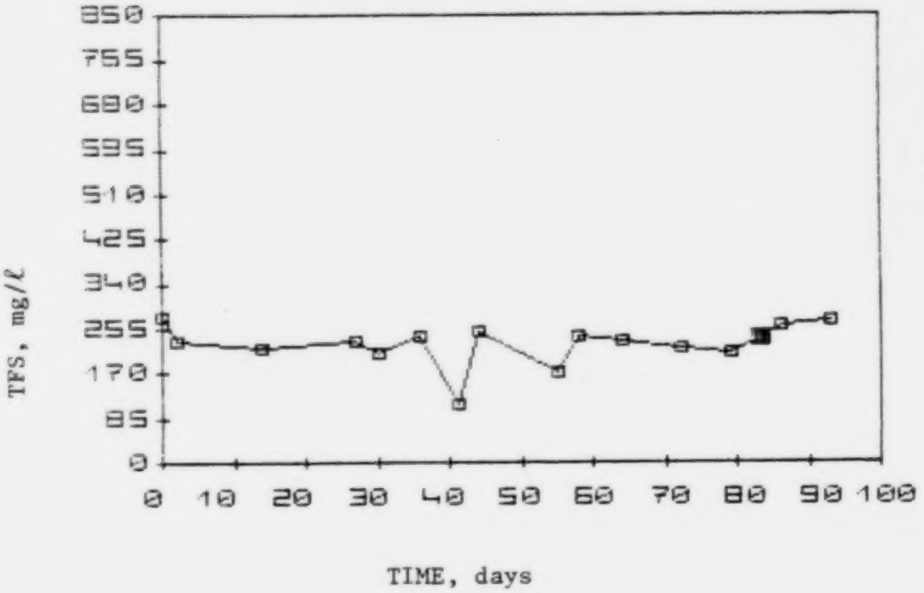


Figure C.65 Total fixed solids concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

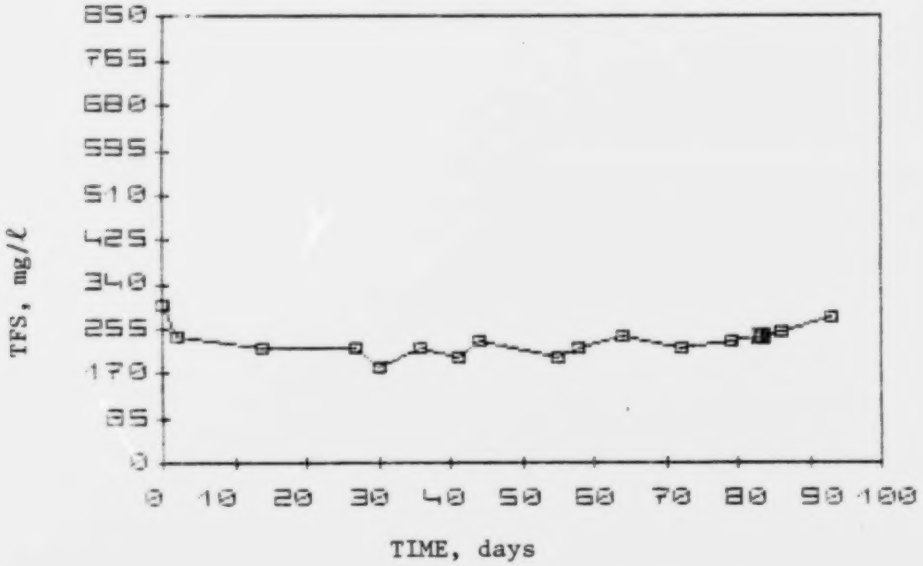


Figure C.66 Total fixed solids concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

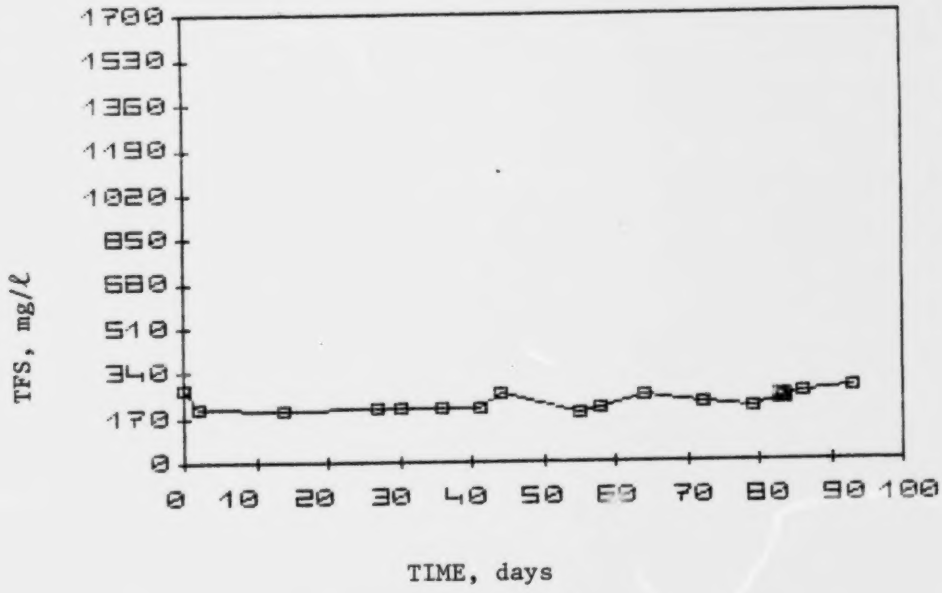


Figure C.67 Total fixed solids concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

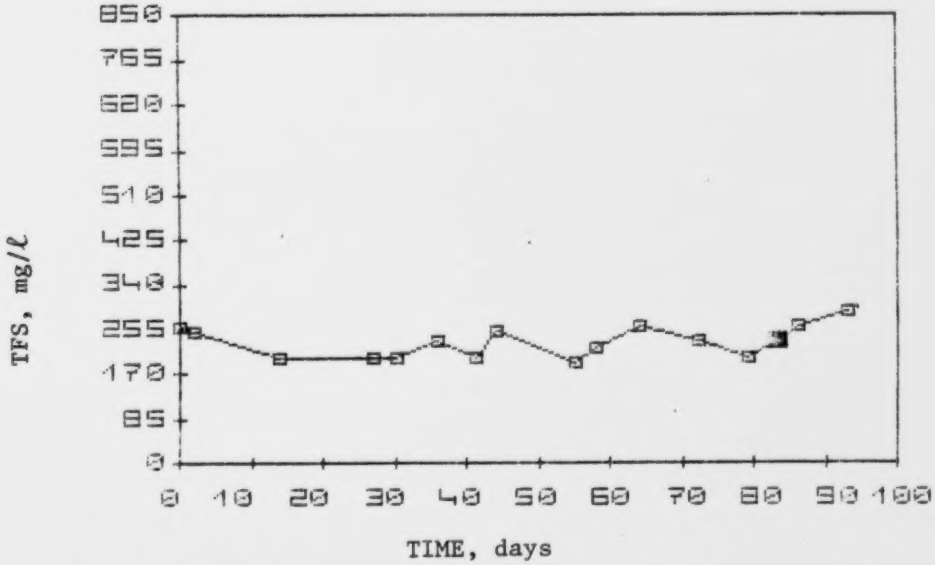
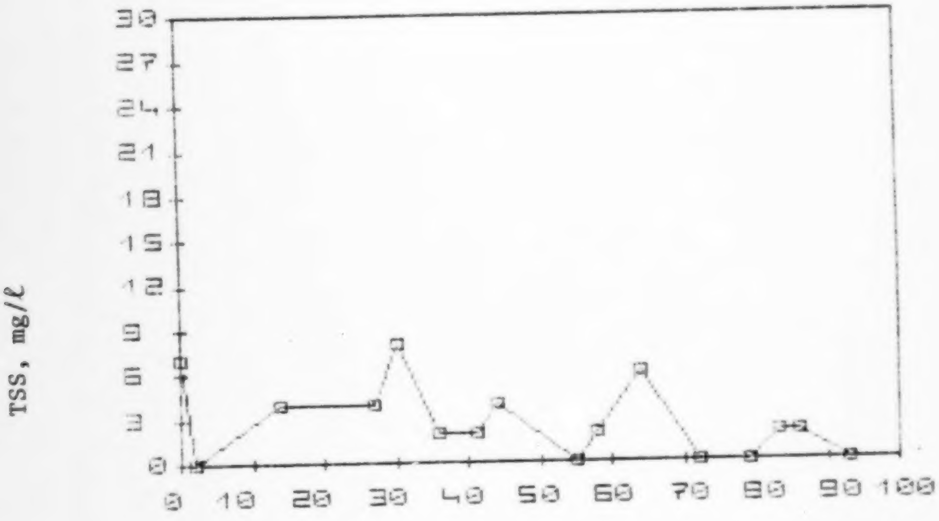
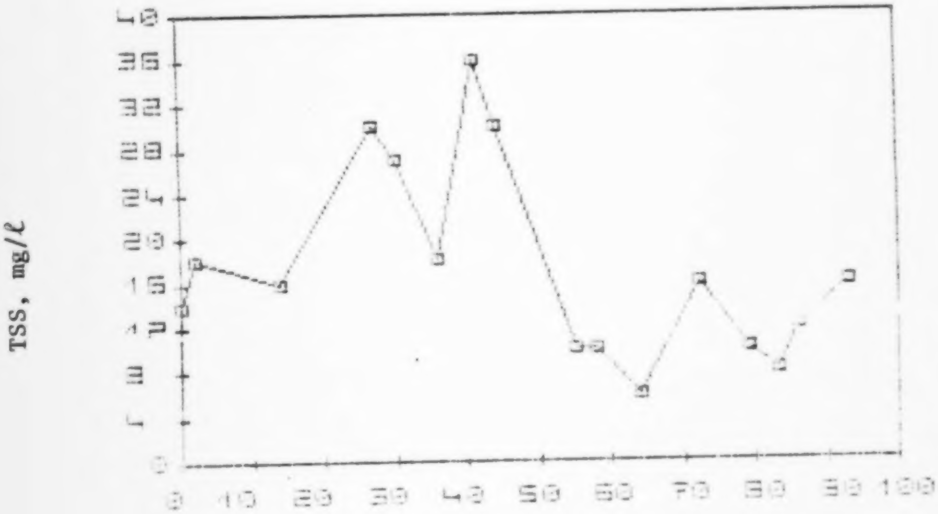


Figure C.68 Total fixed solids concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.



TIME, days

Figure C.69 Total suspended solids concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.



TIME, days

Figure C.70 Total suspended solids concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

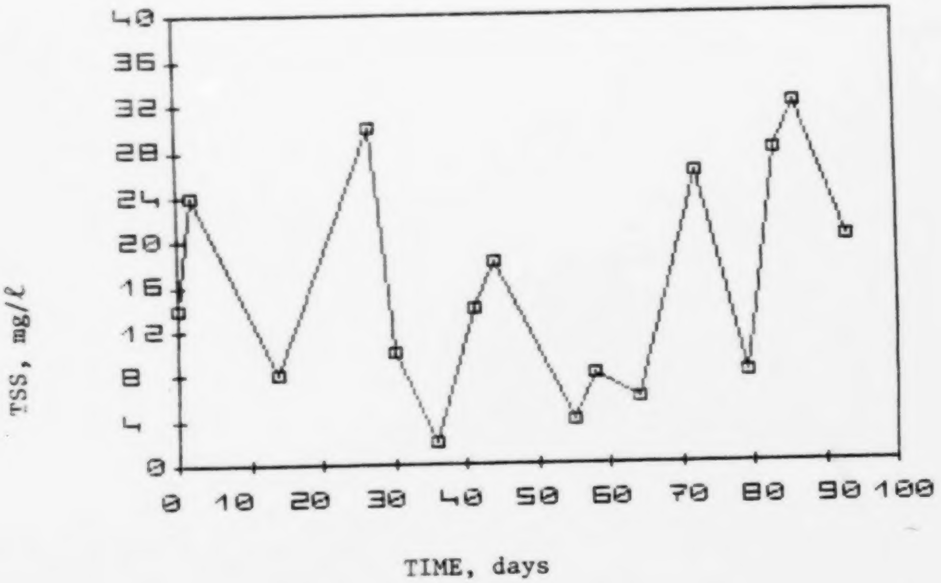


Figure C.71 Total suspended solids concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

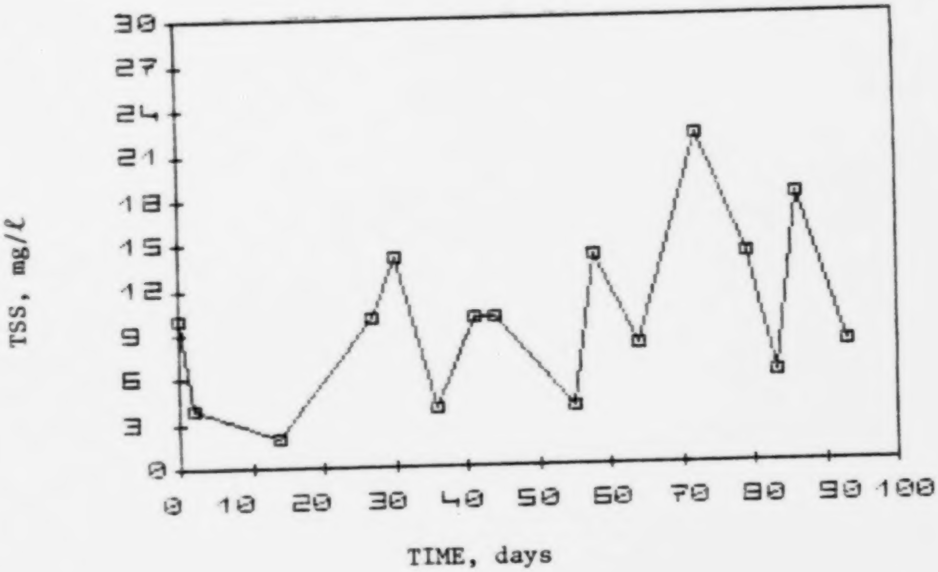


Figure C.72 Total suspended solids concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

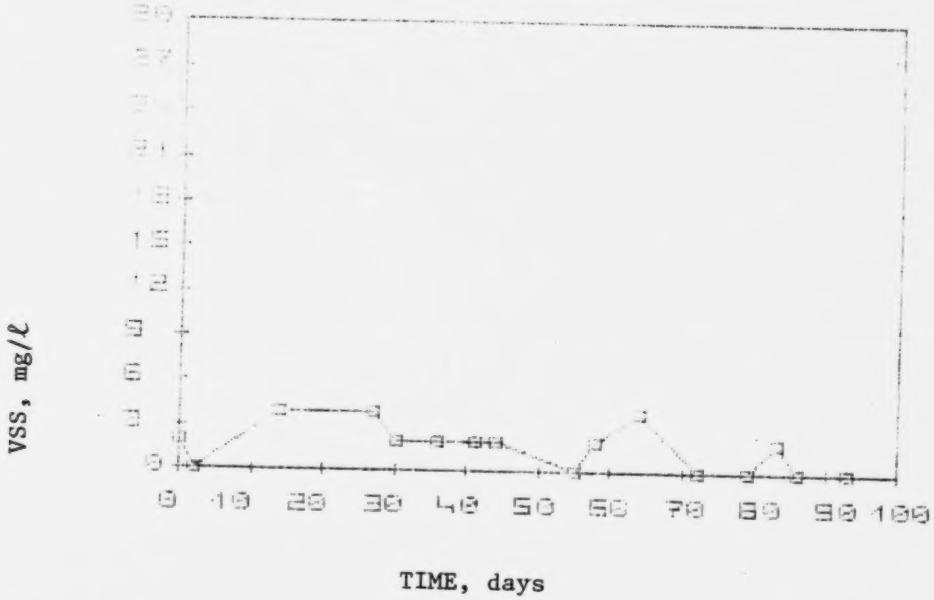


Figure C.73 Volatile suspended solids concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

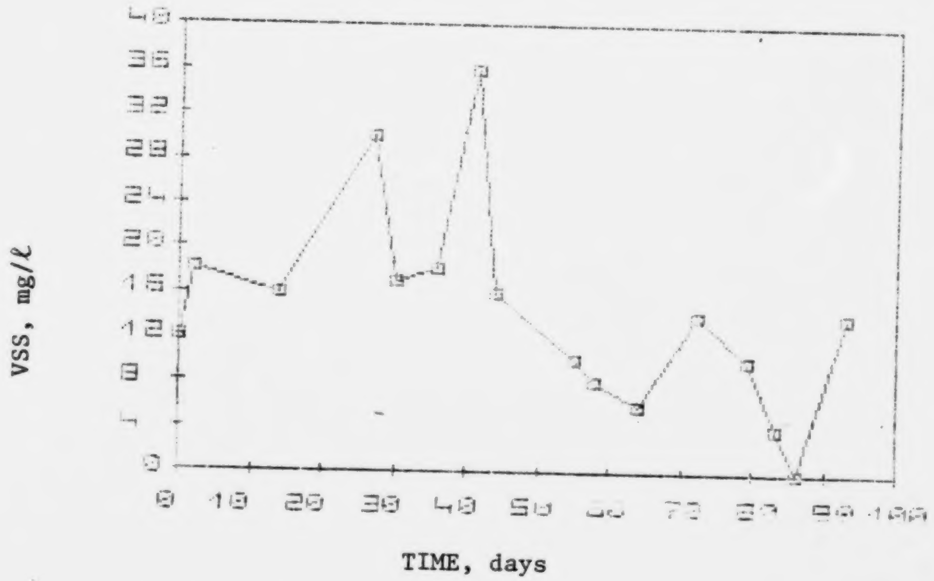


Figure C.74 Volatile suspended solids concentration of snythetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

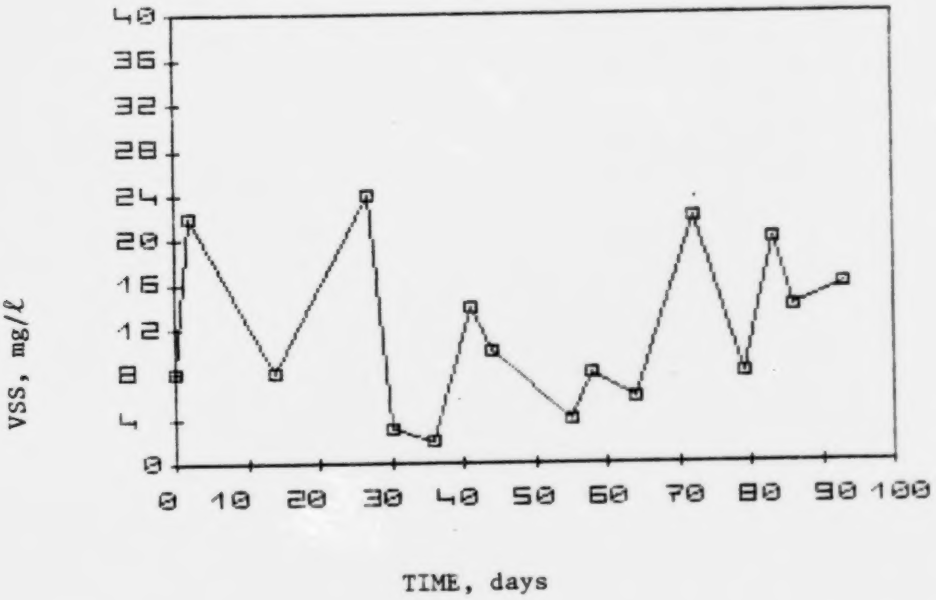


Figure C.75 Volatile suspended solids concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

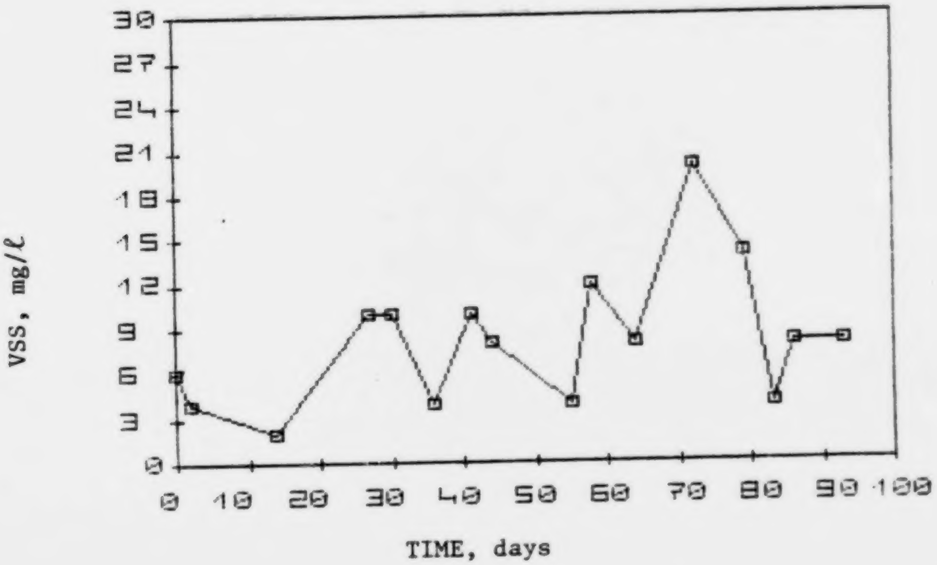


Figure C.76 Volatile suspended solids concentration of effluent synthetic sewage from the Cornell NFT in Pbase 0. First day of analysis was December 5, 1979.

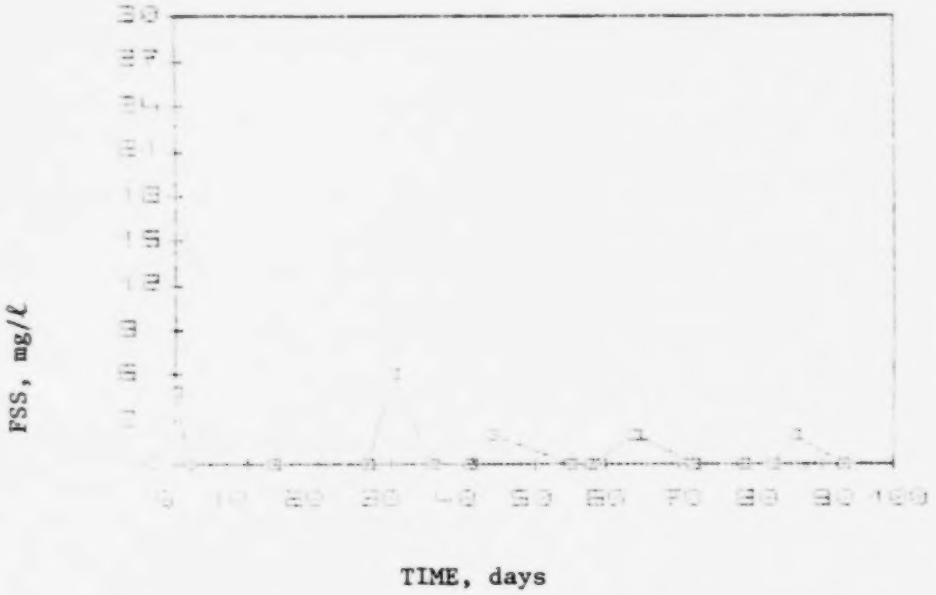


Figure C.77 Fixed suspended solids concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

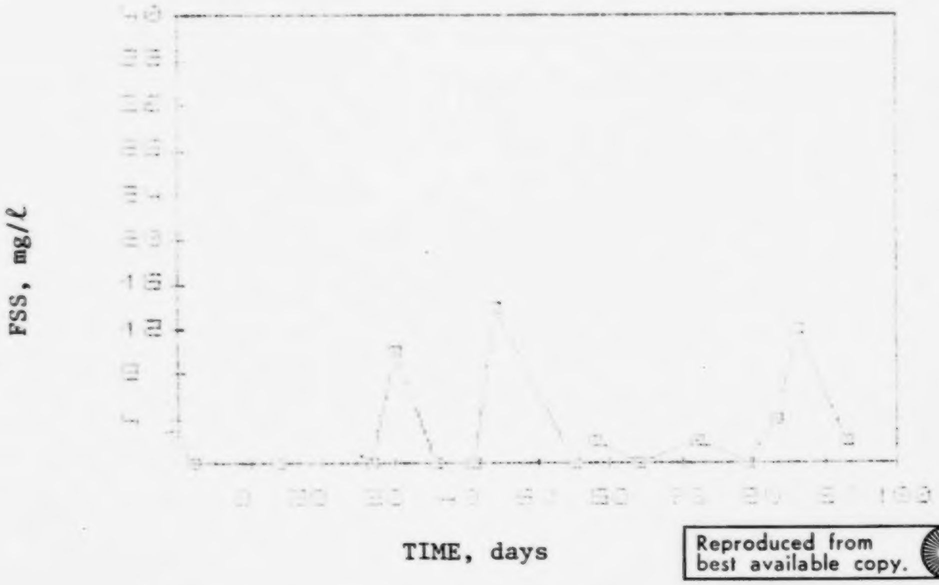


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Figure C.78 Fixed suspended solids concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 1979.

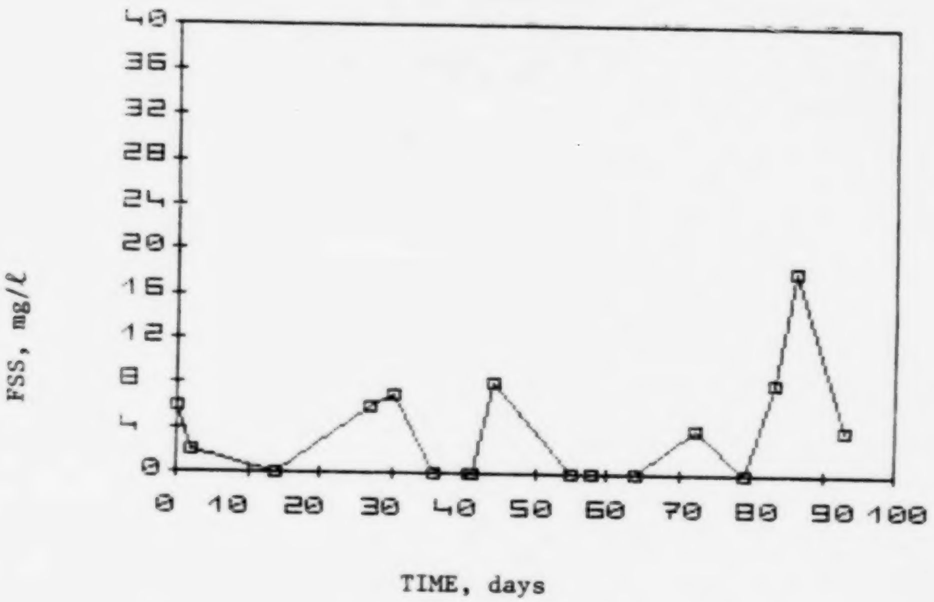

Figure C.79 Fixed suspended solids concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

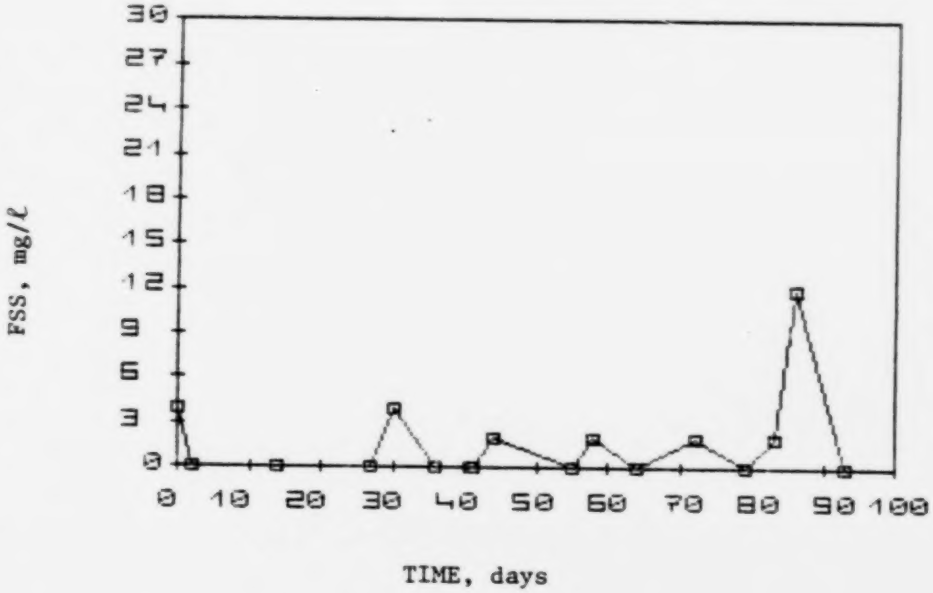

Figure C.80 Fixed suspended solids concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 5, 1979.

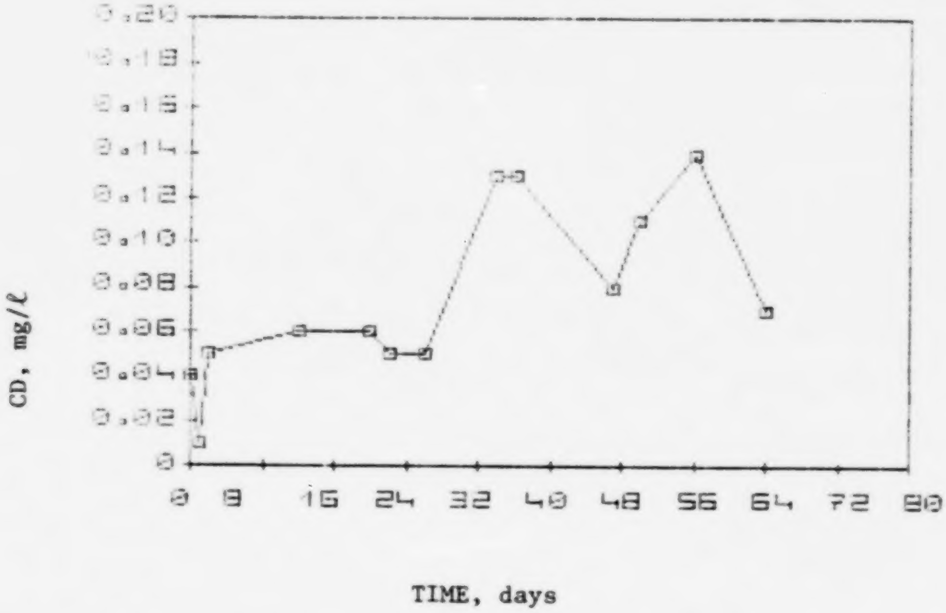

Figure C.81 Cadmium concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

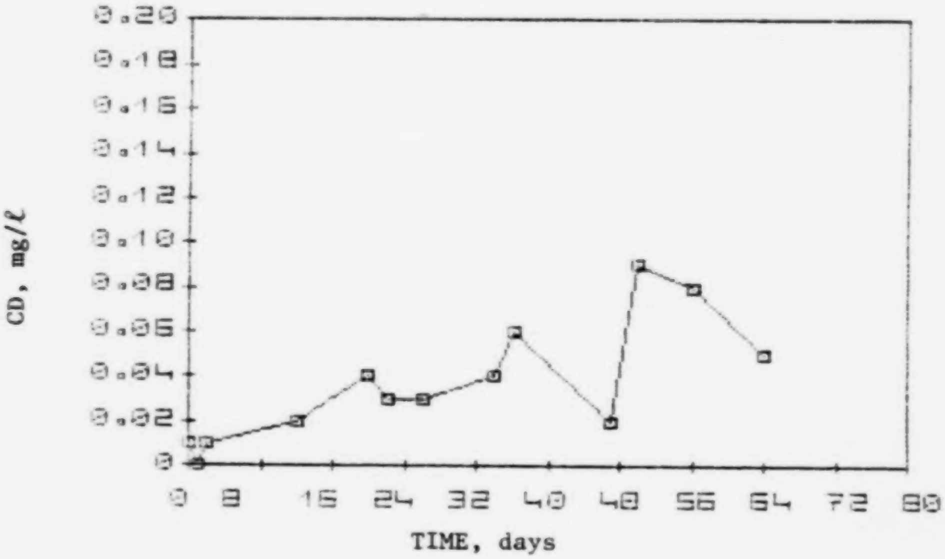

Figure C.82 Cadmium concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

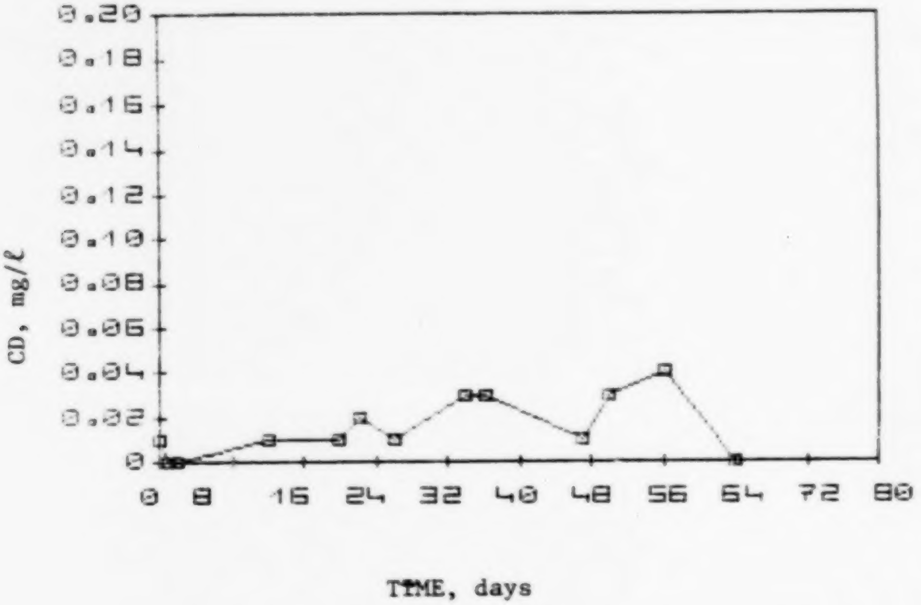

Figure C.83 Cadmium concentration of synthetic sewage at Point B in the Cornell NFT in Phase O. First day of analysis was December 7, 1979.

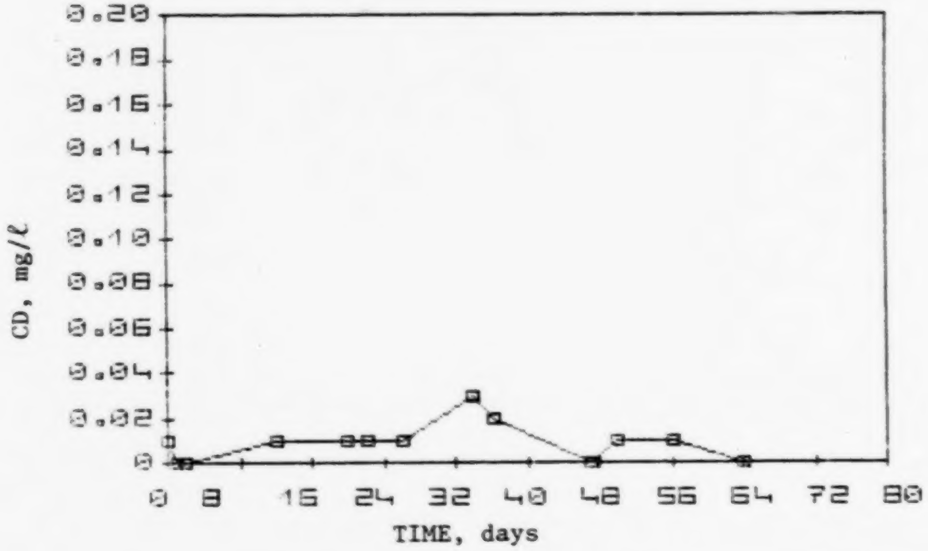

Figure C.84 Cadmium concentration of effluent synthetic sewage from the Cornell NFT in Phase O. First day of analysis was December 7, 1979.

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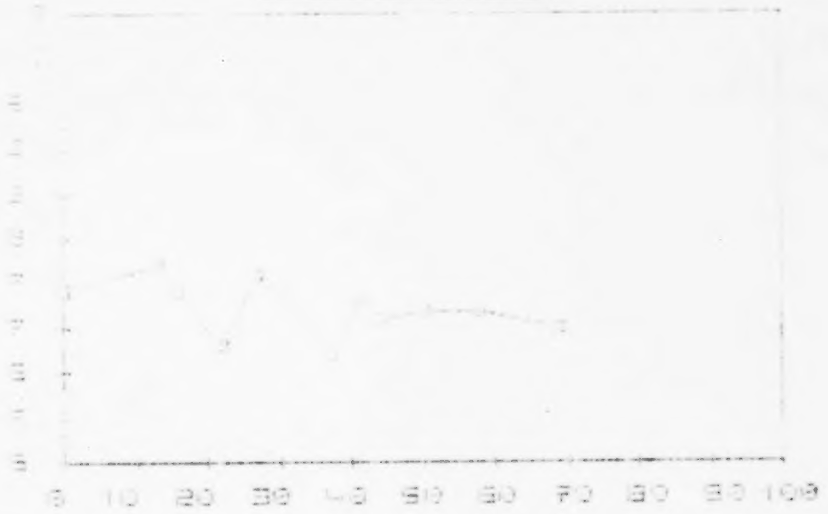
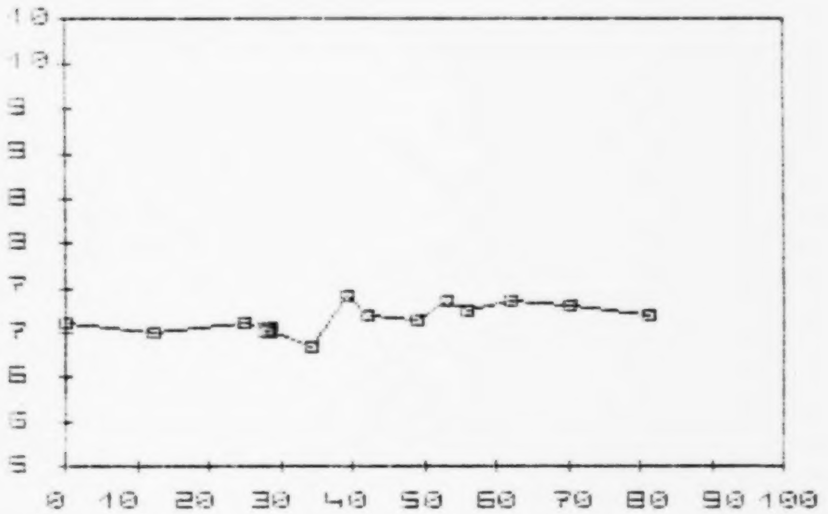


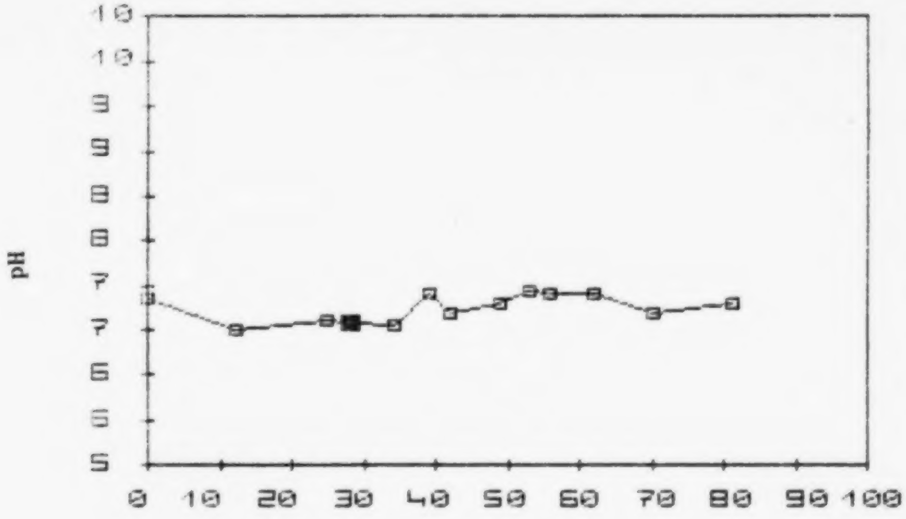
TIME, days

Figure C.85 pH of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.



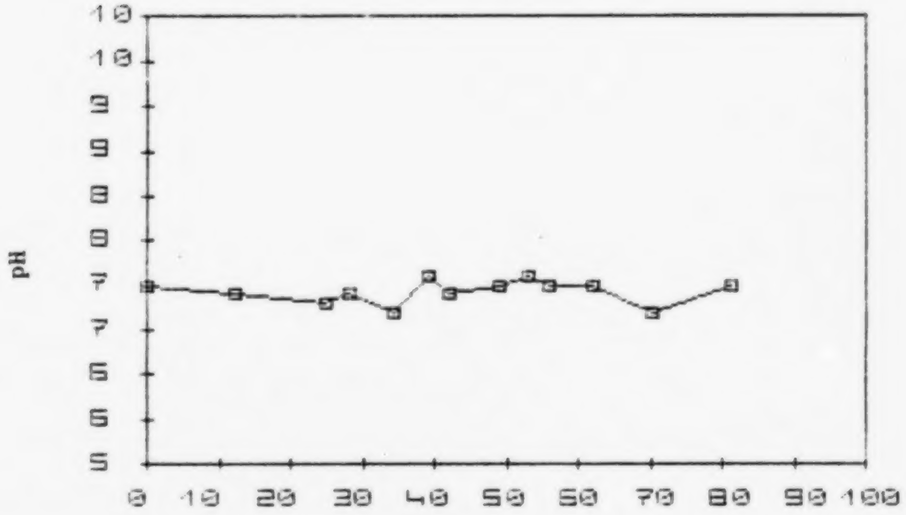
TIME, days

Figure C.86 pH of snythetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.



TIME, days

Figure C.87 pH of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.



TIME, days

Figure C.88 pH of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

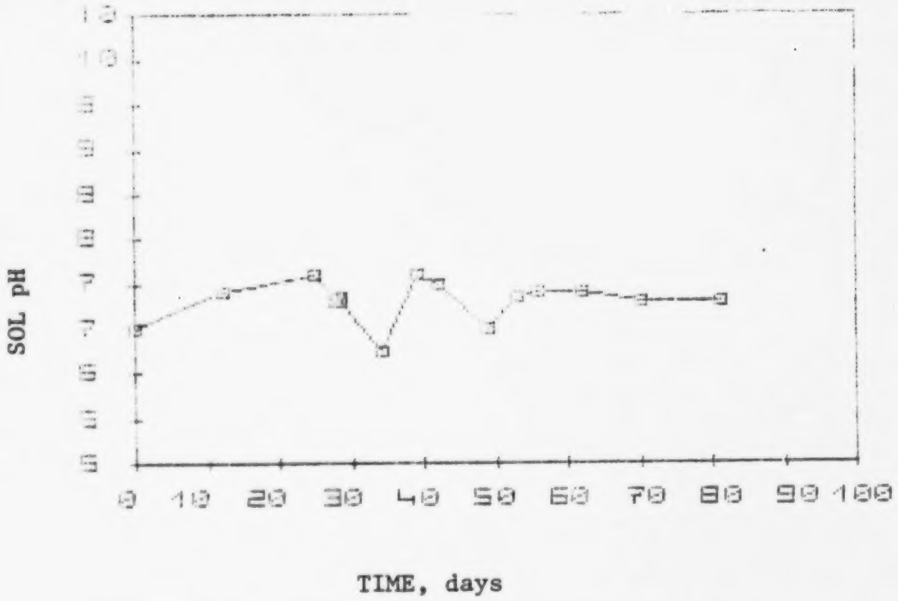


Figure C.89 Soluble pH of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

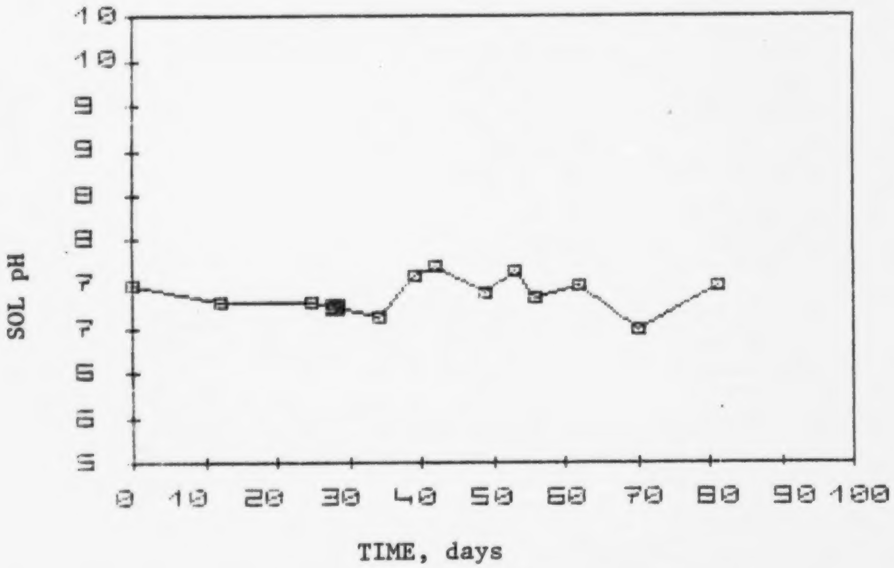


Figure C.90 Soluble pH of influent synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

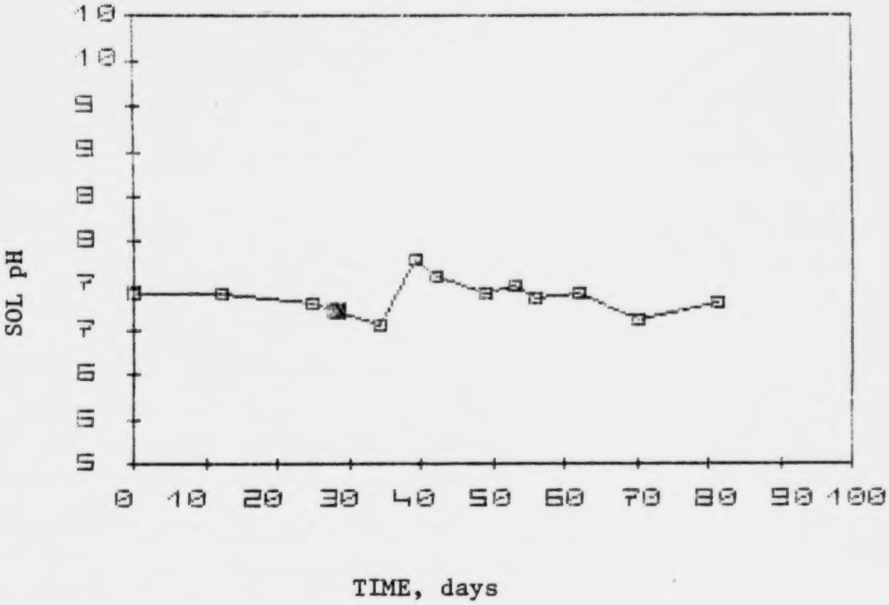


Figure C.91 Soluble pH of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

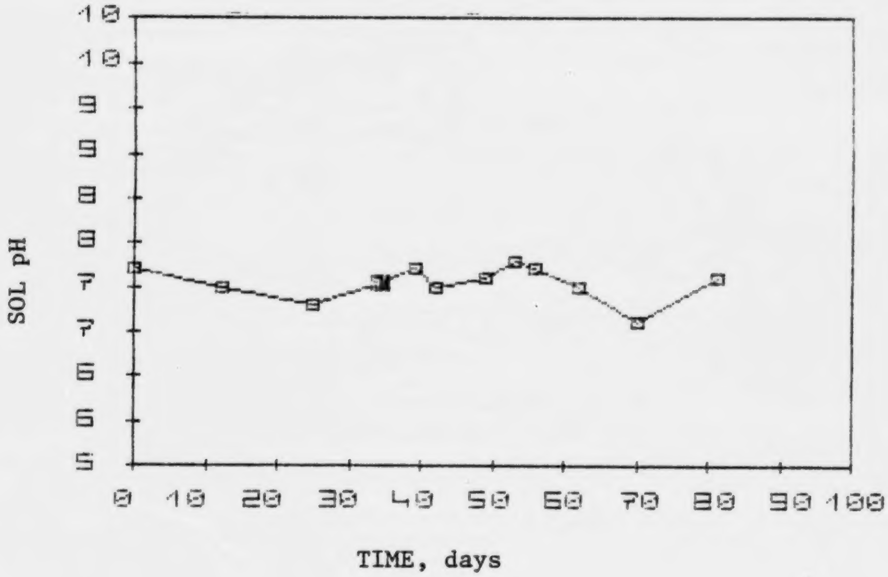


Figure C.92 Soluble pH of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 7, 1979.

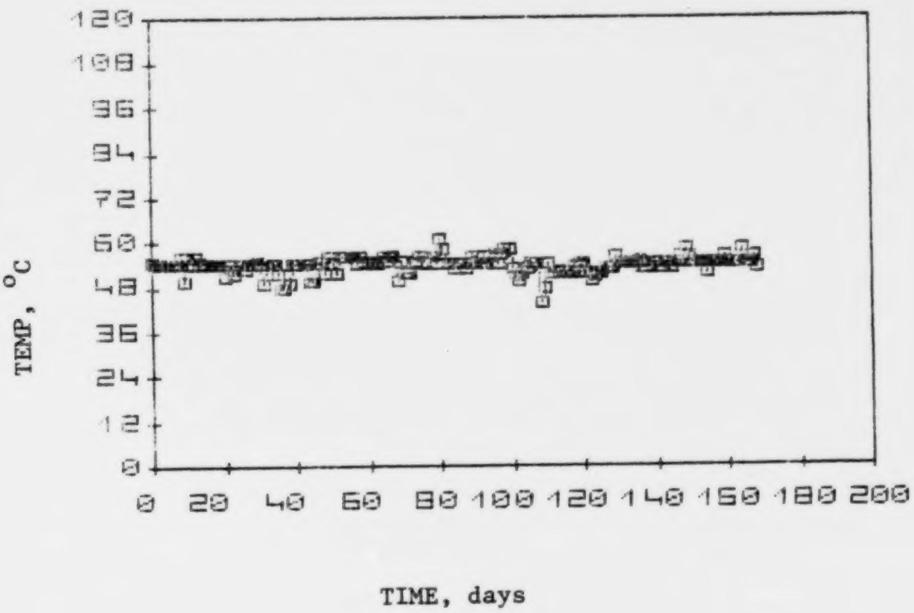


Figure C.93 Minimum daily air temperature in the Cornell NFT greenhouse in Phase 0. First day of measurement was November 12, 1979.

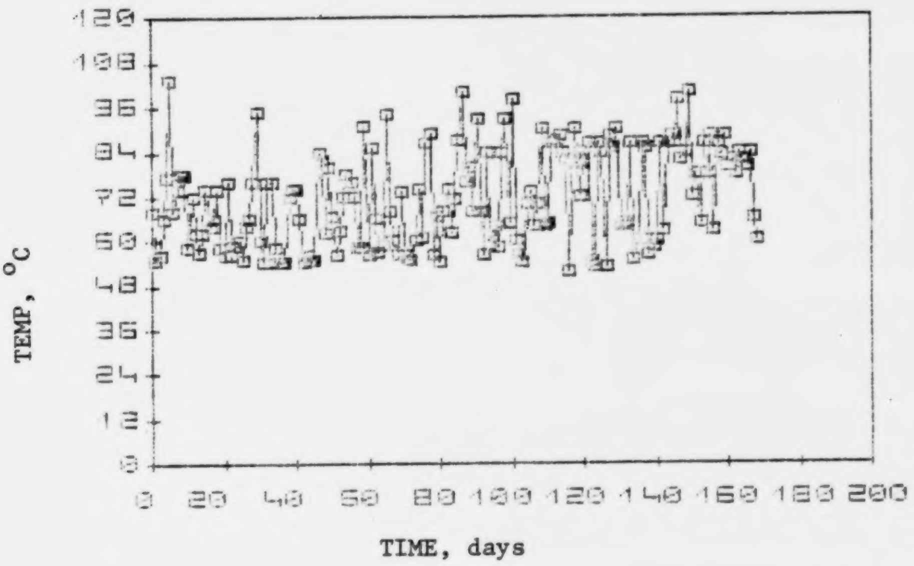
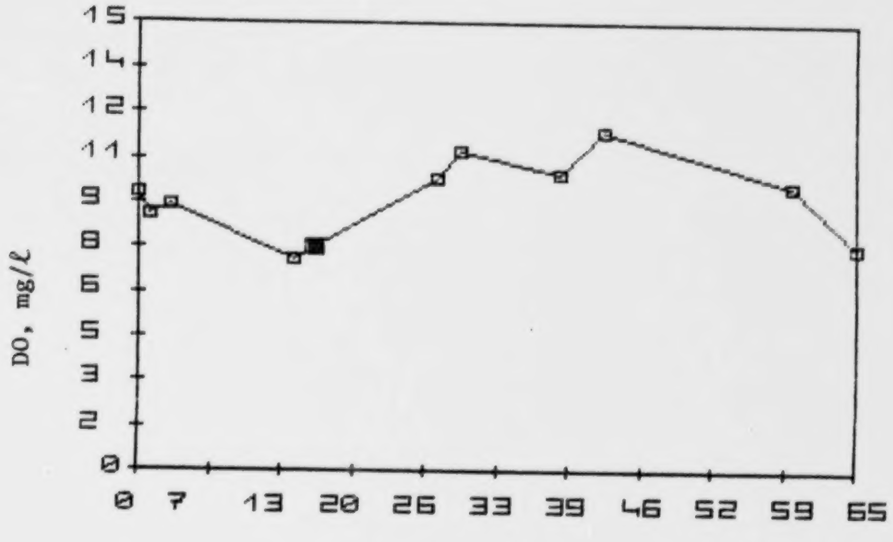
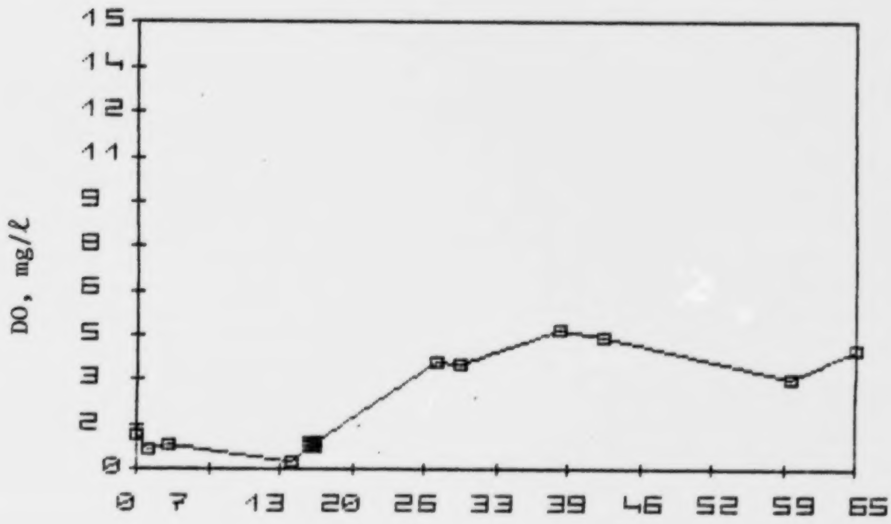


Figure C.94 Maximum daily air temperature in the Cornell NFT greenhouse in Phase 0. First day of measurement was November 12, 1979.



TIME, days

Figure C.95 Dissolved oxygen concentration of influent synthetic sewage to the Cornell NFT in Phase 0. First day of analysis was December 18, 1979.



TIME, days

Figure C.96 Dissolved oxygen concentration of synthetic sewage at Point A in the Cornell NFT in Phase 0. First day of analysis was December 18, 1979.

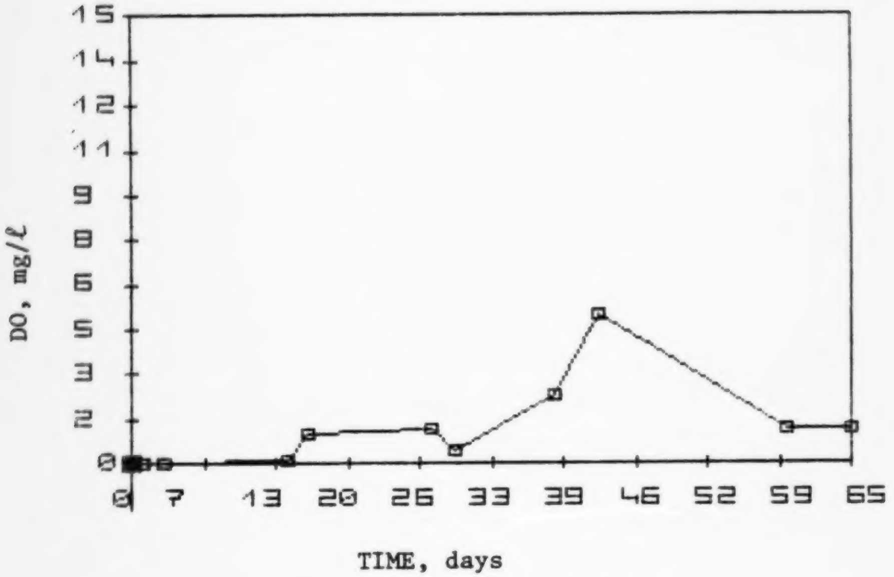


Figure C.97 Dissolved oxygen concentration of synthetic sewage at Point B in the Cornell NFT in Phase 0. First day of analysis was December 18, 1979.

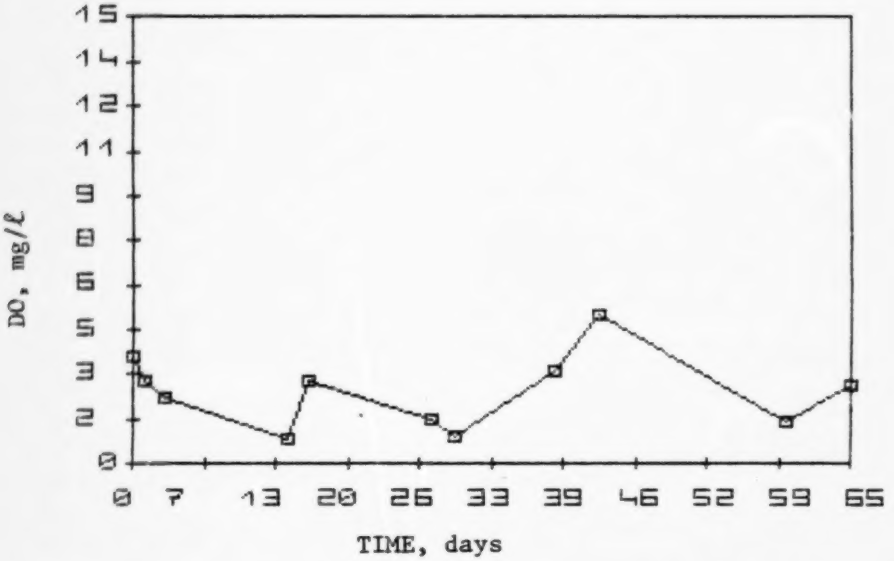


Figure C.98 Dissolved oxygen concentration of effluent synthetic sewage from the Cornell NFT in Phase 0. First day of analysis was December 18, 1979.

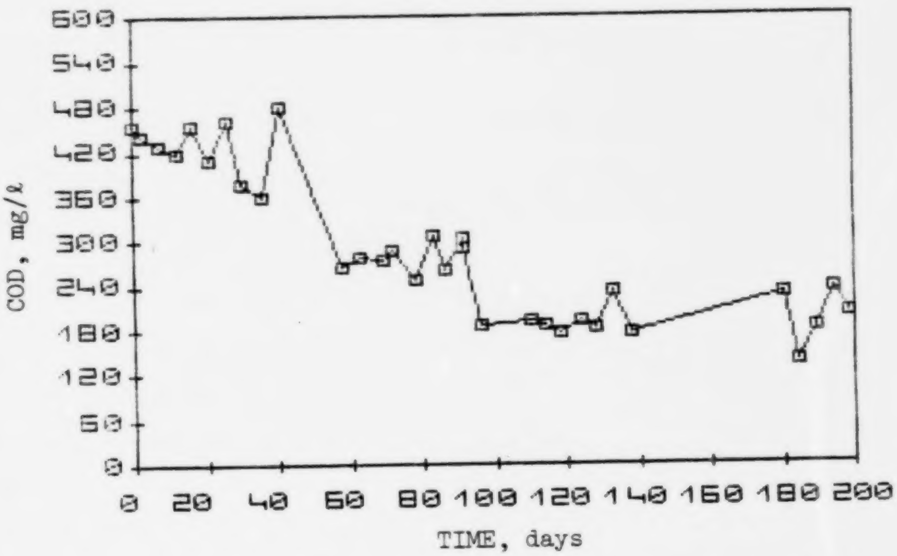


Figure C.99. Chemical oxygen demand concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

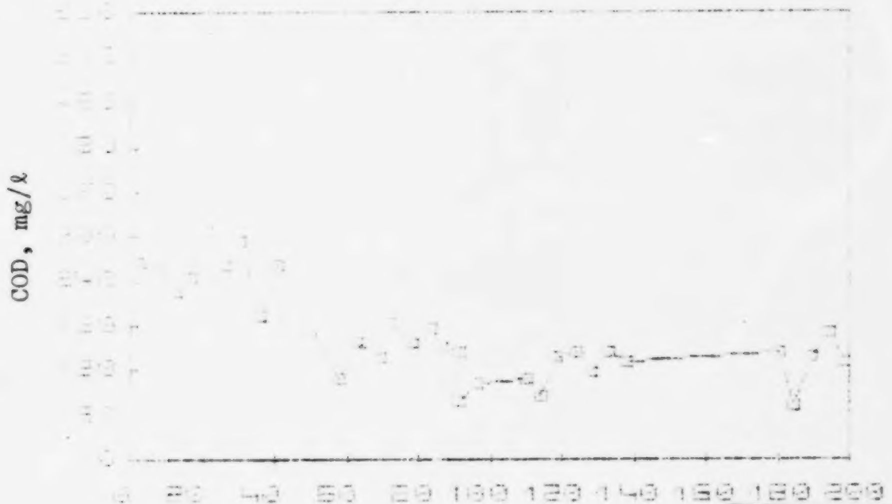


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Figure C.100. Chemical oxygen demand concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

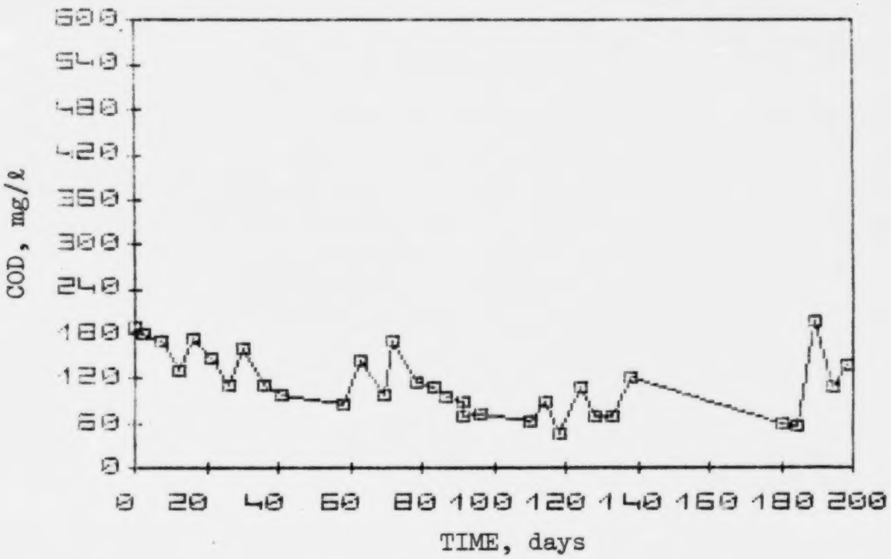

Figure C.101. Chemical oxygen demand concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

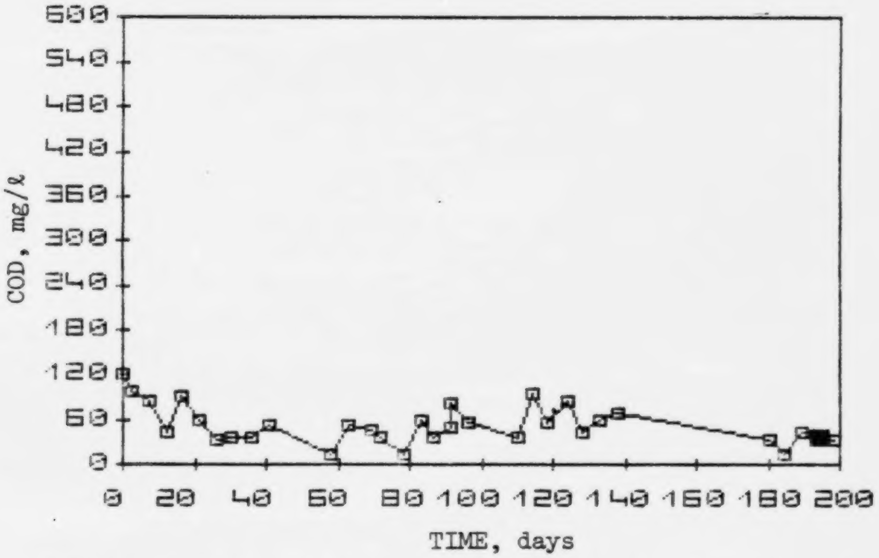

Figure C.102. Chemical oxygen demand concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

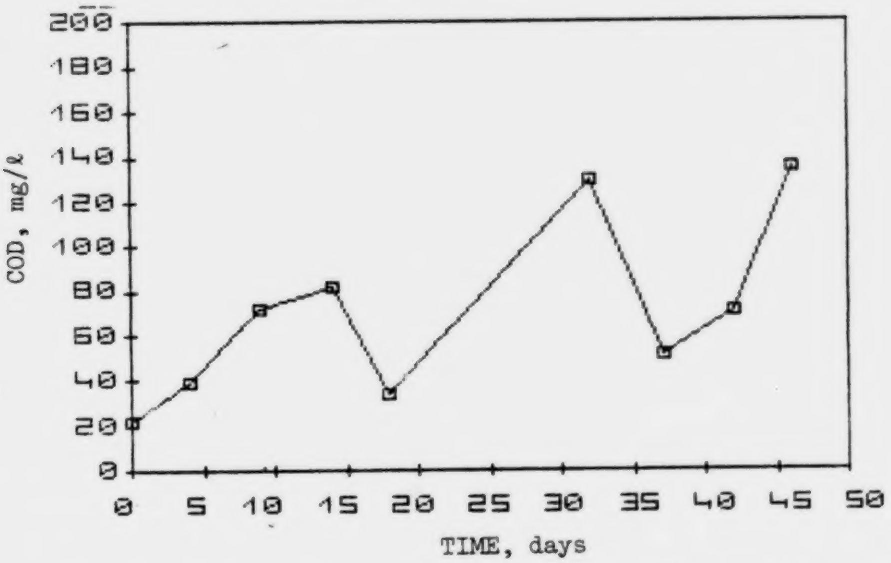

Figure C.103. Chemical oxygen demand concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

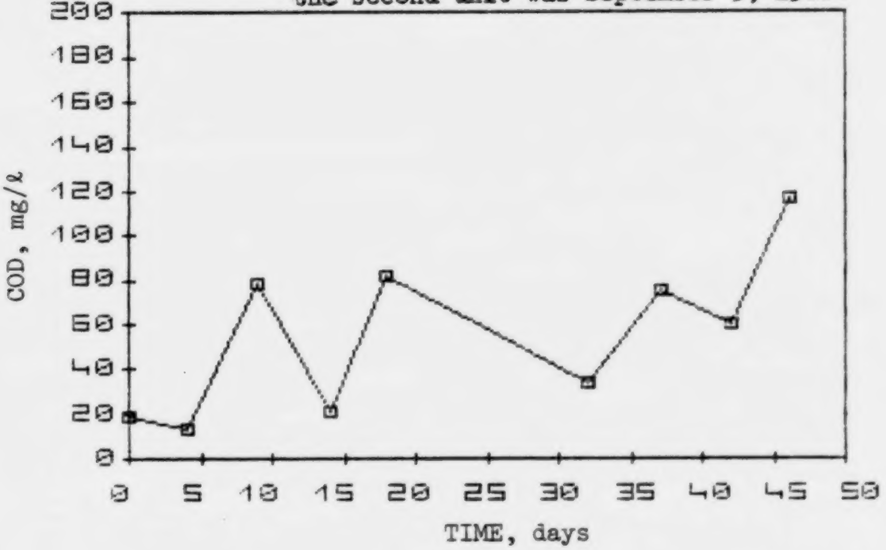

Figure C.104. Chemical oxygen demand concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT unit in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

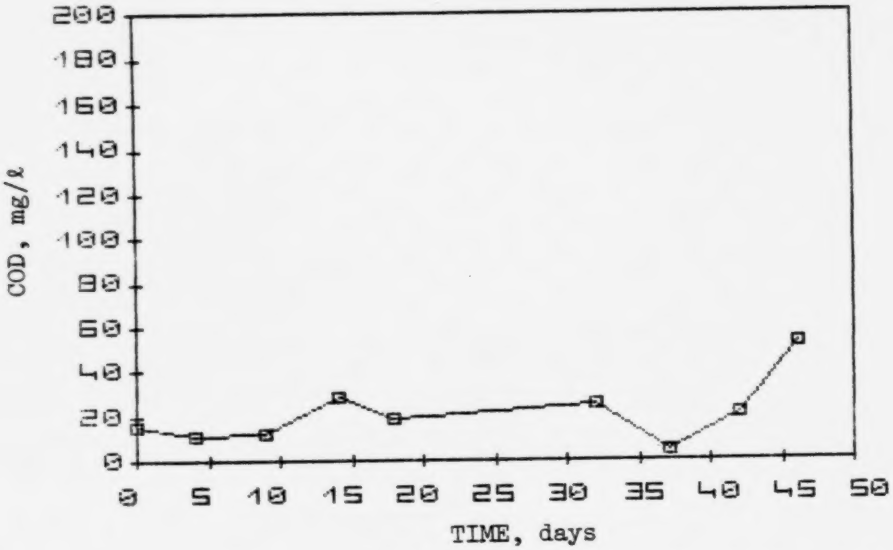

Figure C.105. Chemical oxygen demand concentration of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

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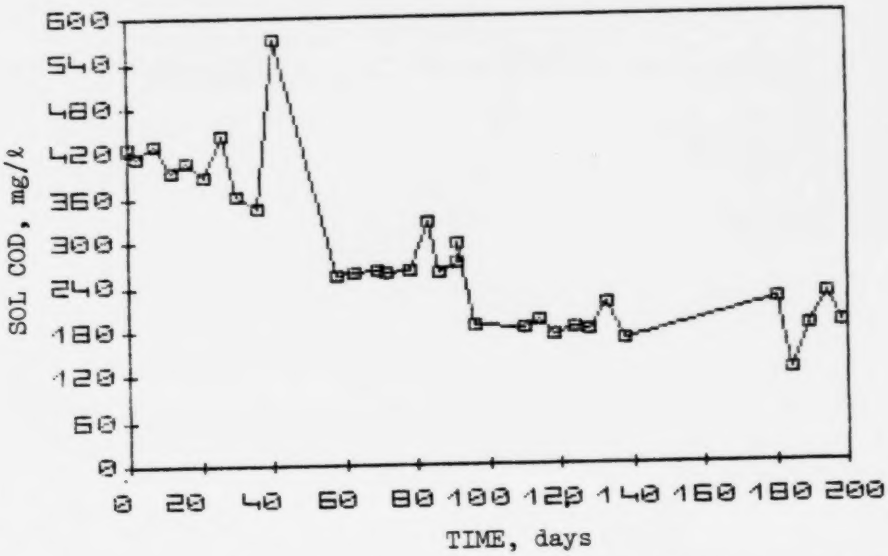

Figure C.106. Soluble chemical oxygen demand concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

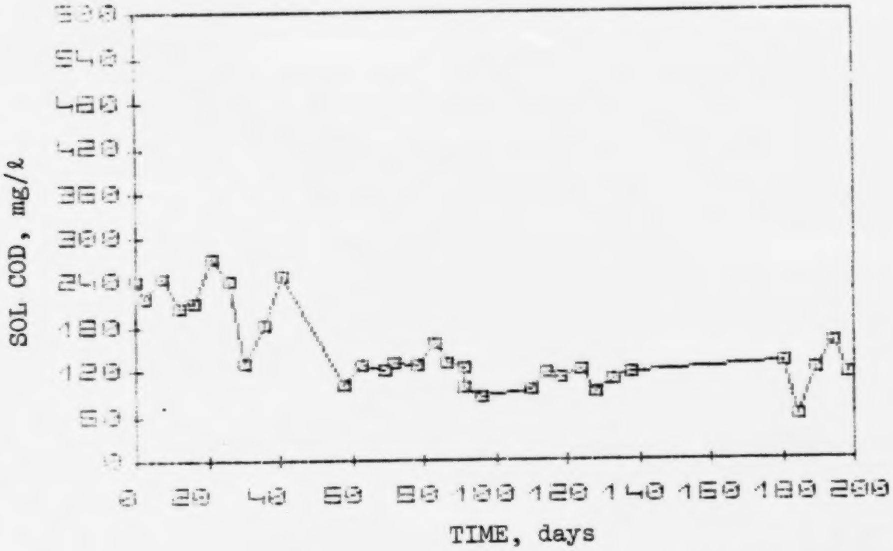

Figure C.107. Soluble chemical oxygen demand concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

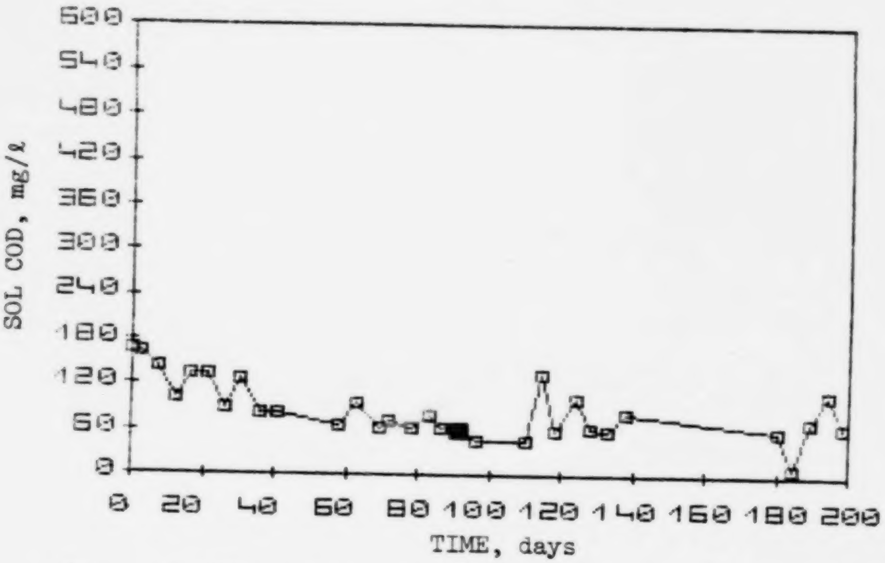

Figure C.108. Soluble chemical oxygen demand concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

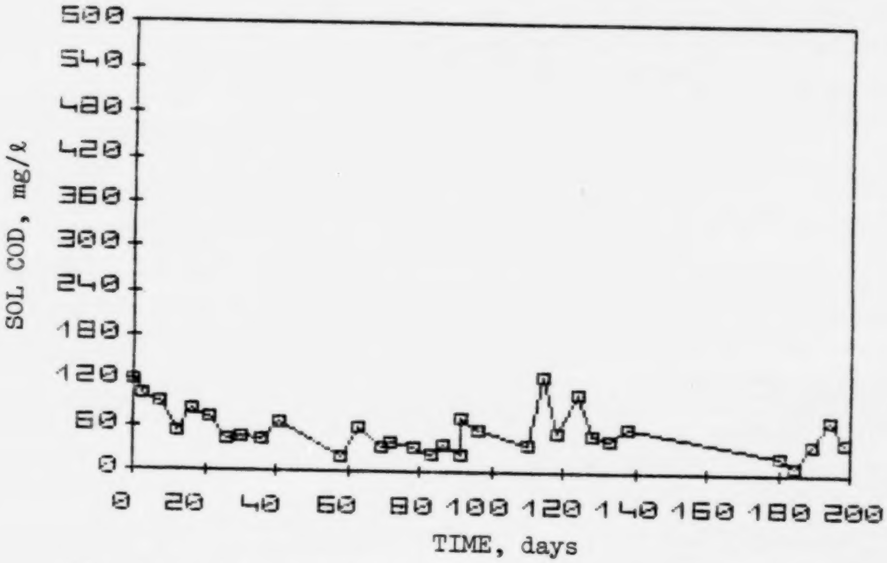

Figure C.109. Soluble chemical oxygen demand concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

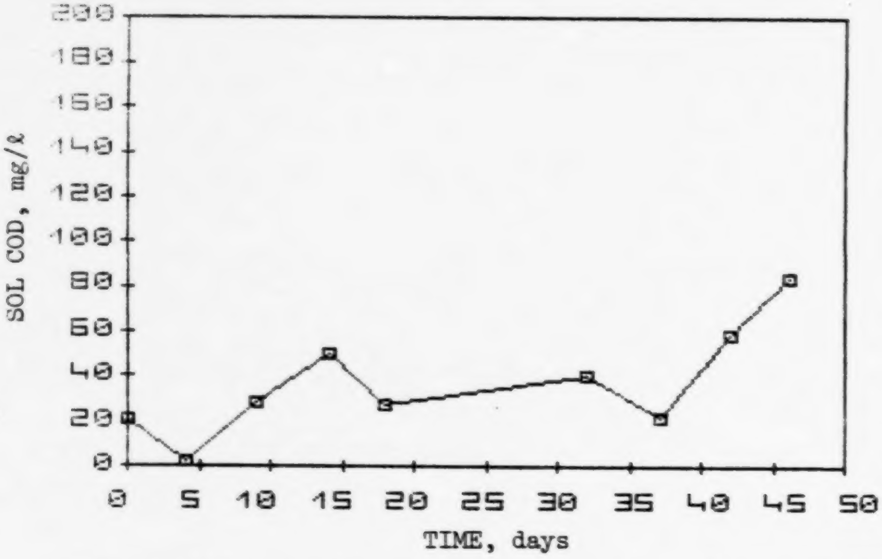

Figure C.110. Soluble chemical oxygen demand concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1982.

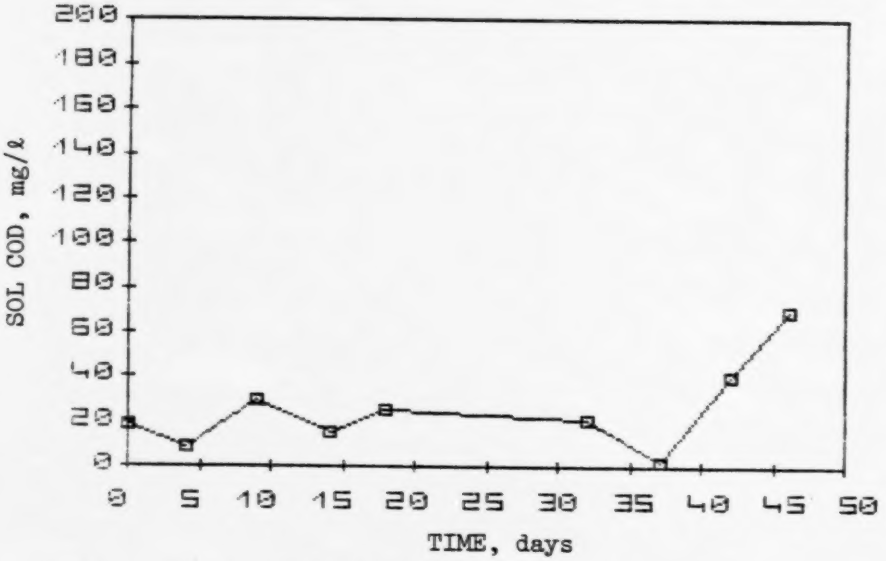

Figure C.111. Soluble chemical oxygen demand concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

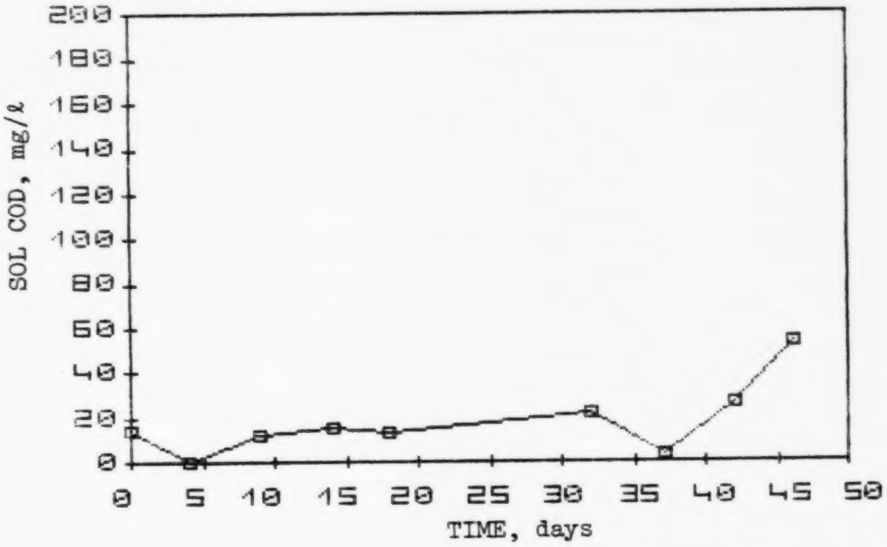

Figure C.112. Soluble chemical oxygen demand concentration of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

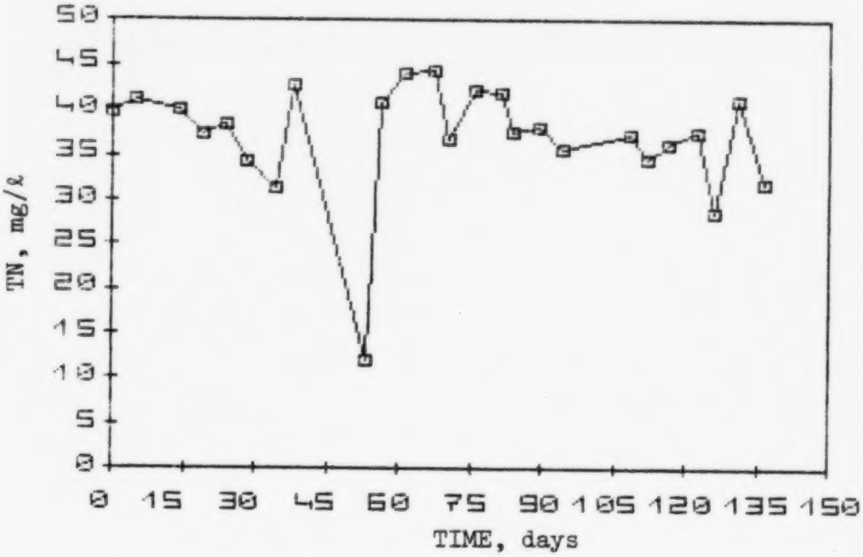

Figure C.113. Total nitrogen concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

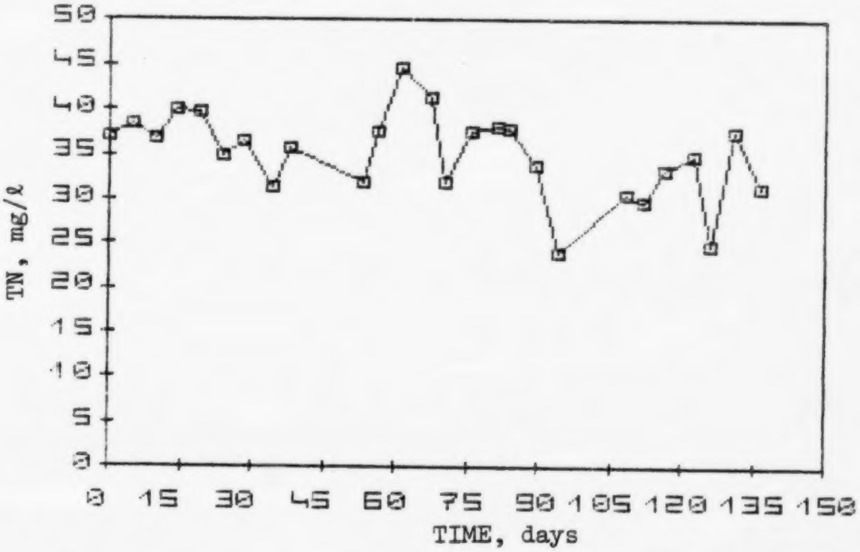

Figure C.114. Total nitrogen concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

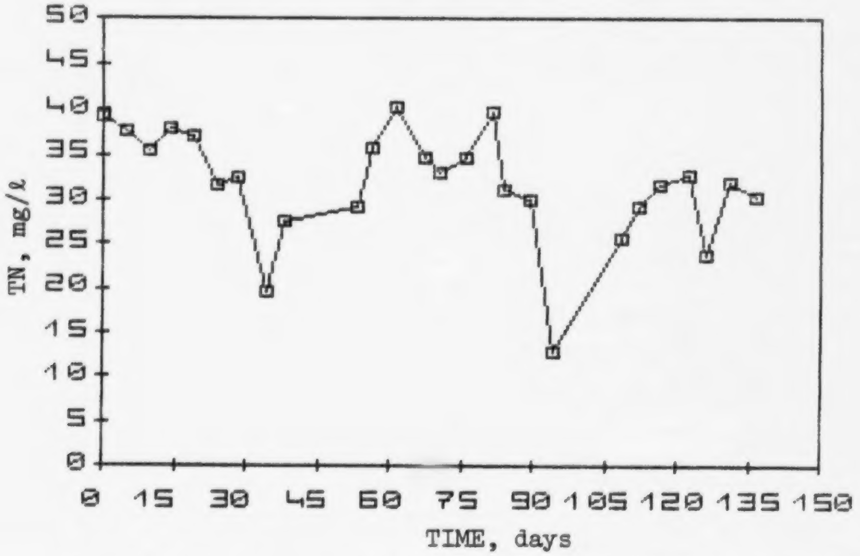

Figure C.115. Total nitrogen concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

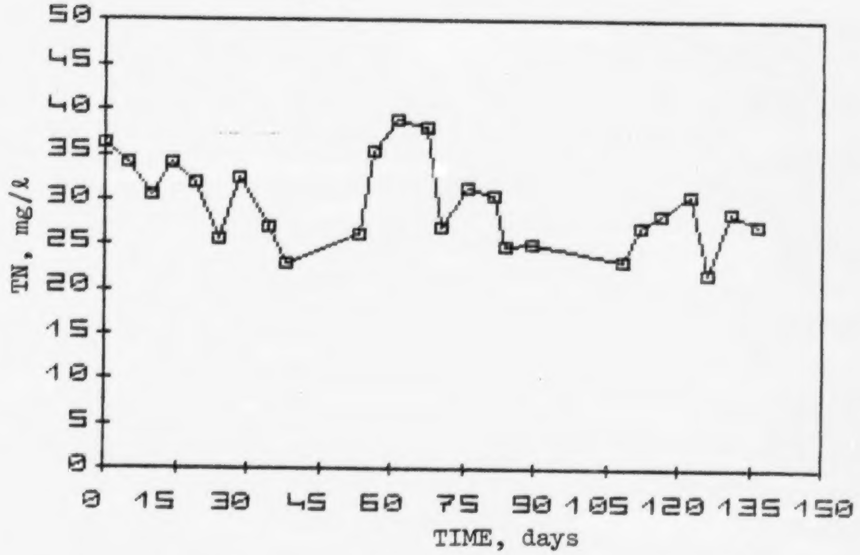

Figure C.116. Total nitrogen concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

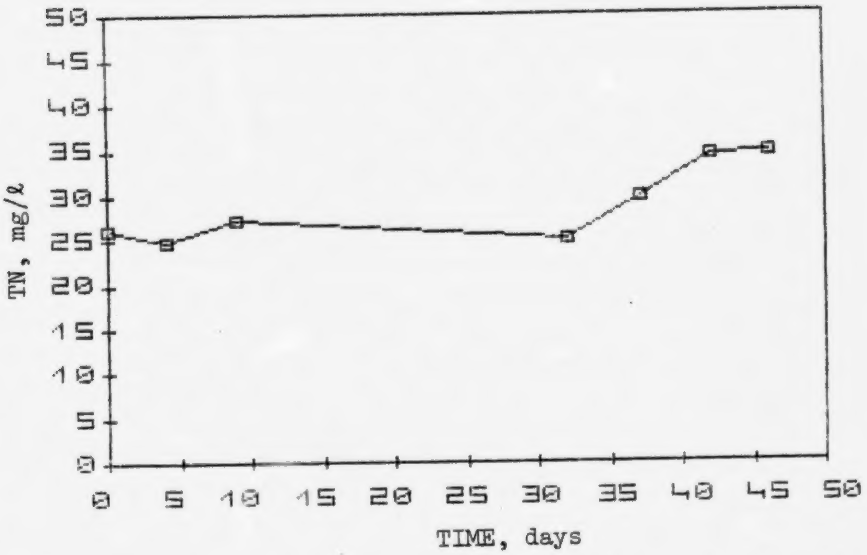

Figure C.117. Total nitrogen concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

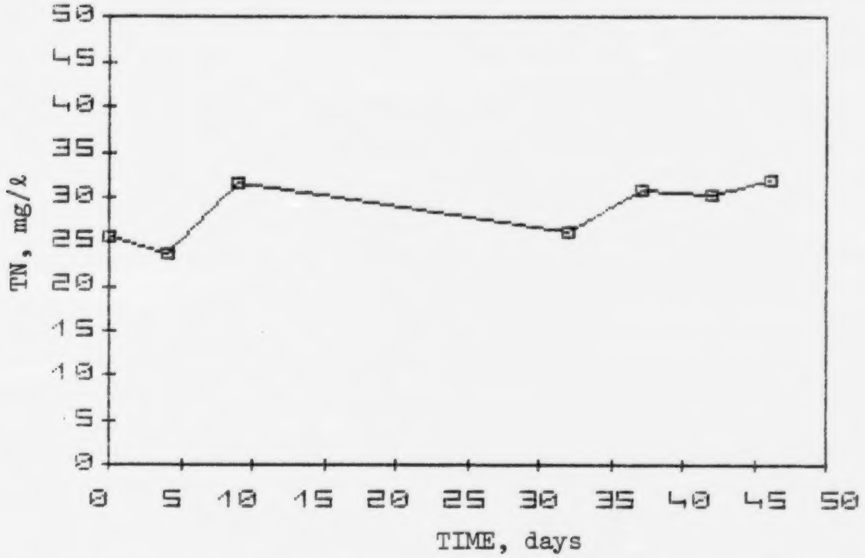

Figure C.118. Total nitrogen concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

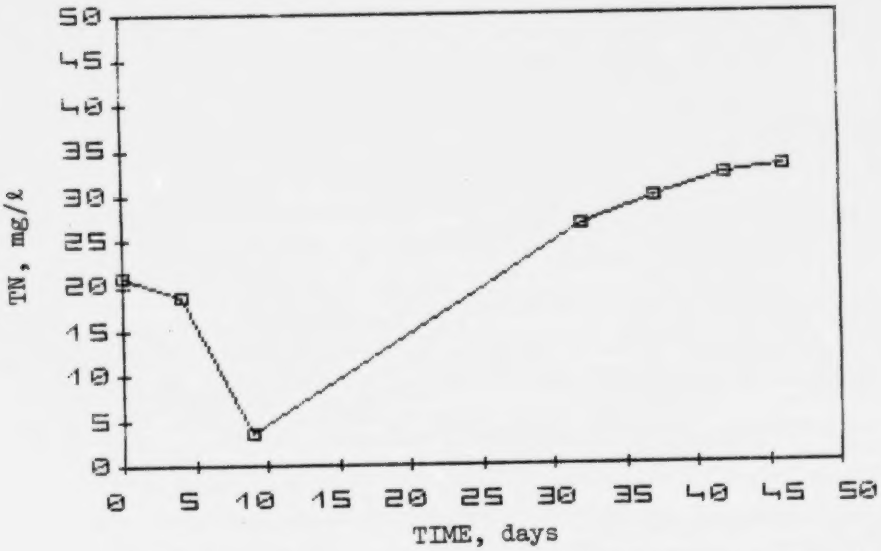

Figure C.119. Total nitrogen concentration of effluent synthetic sewage in the second unit of two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

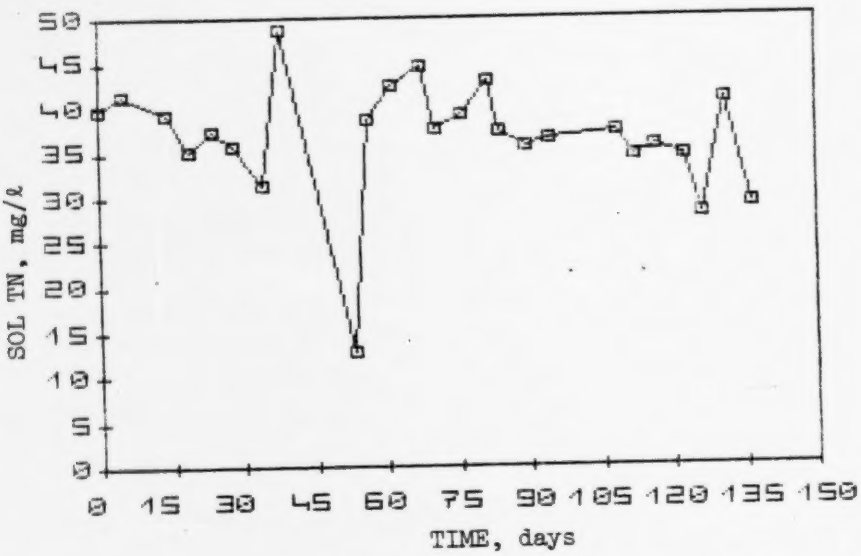

Figure C.120. Soluble total nitrogen concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

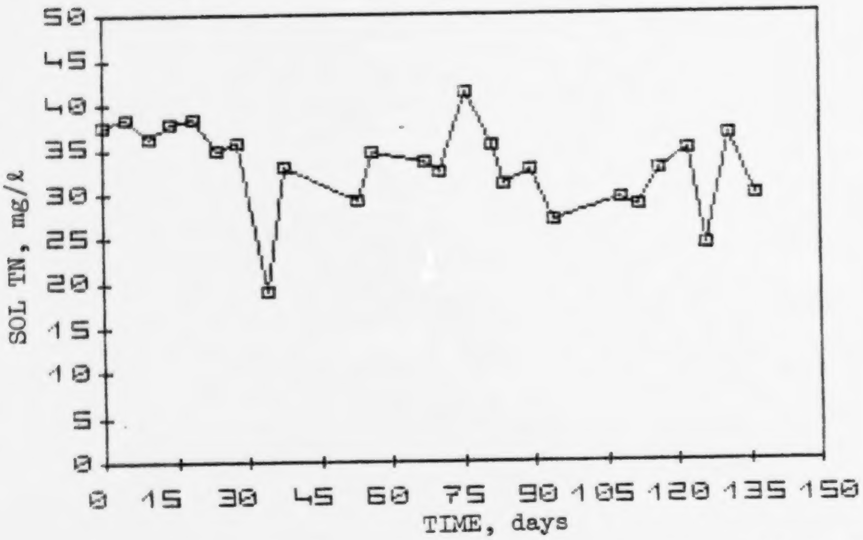

Figure C.121. Soluble total nitrogen concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

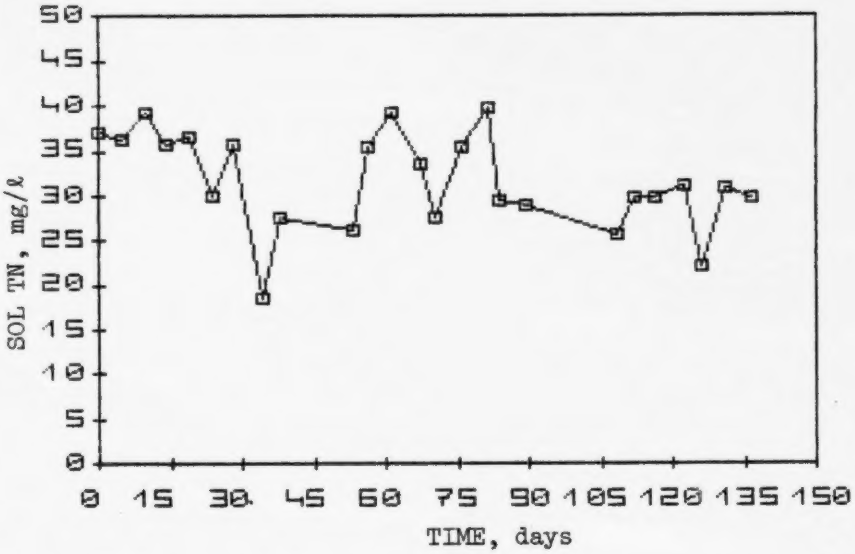

Figure C.122. Soluble total nitrogen concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

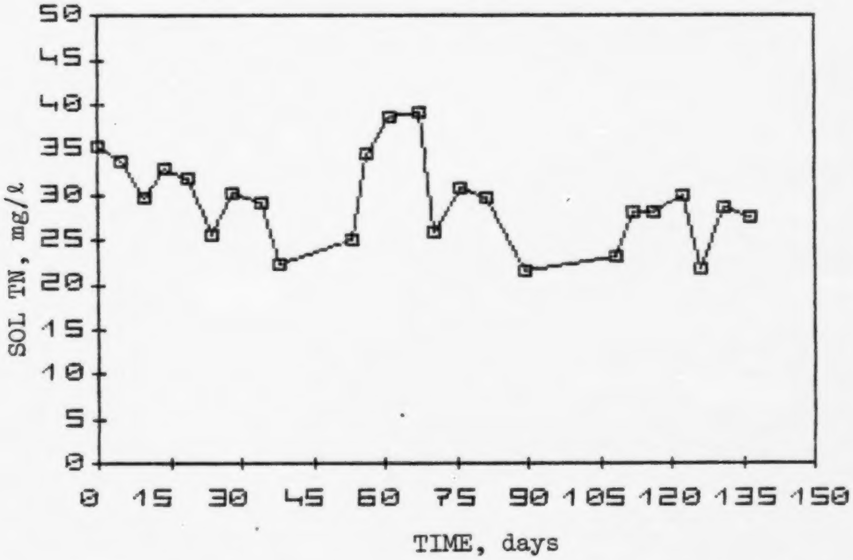

Figure C.123. Soluble total nitrogen concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

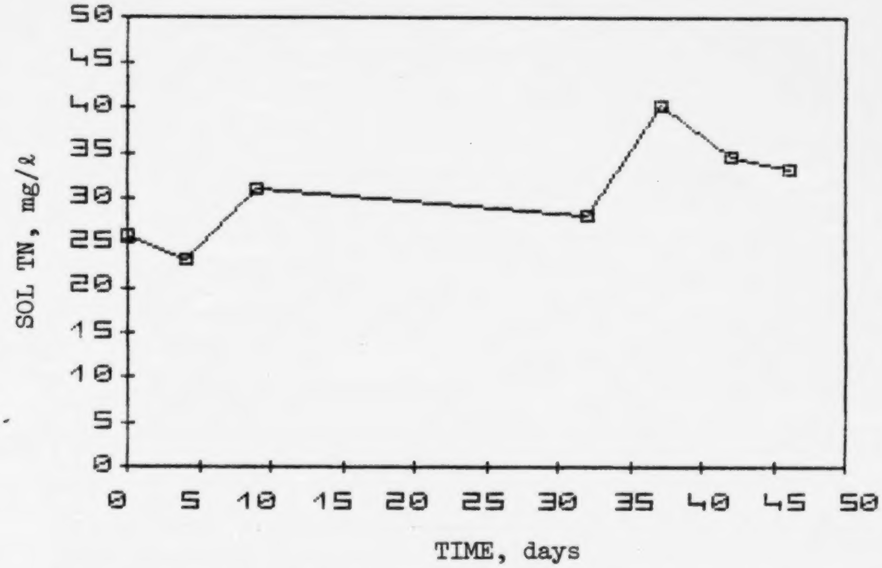

Figure C.124. Soluble total nitrogen concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

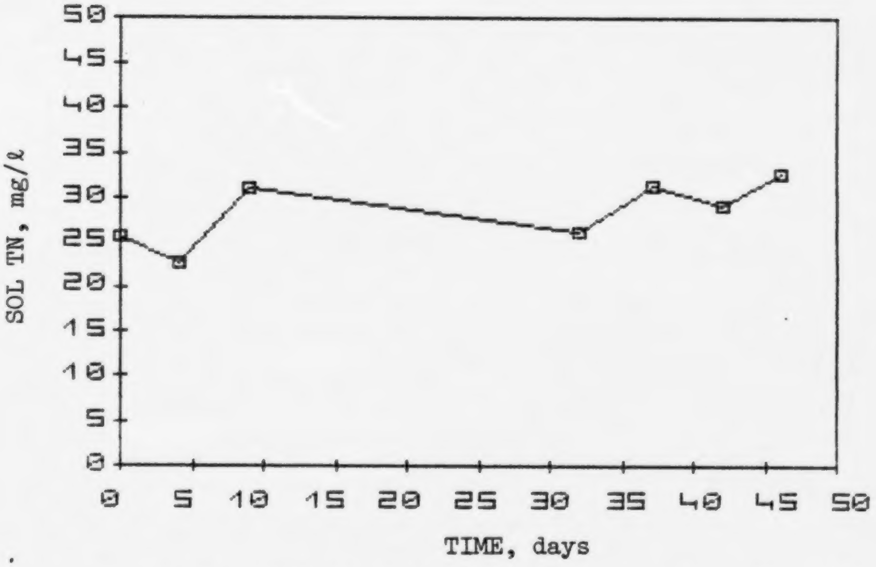

Figure C.125. Soluble total nitrogen concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

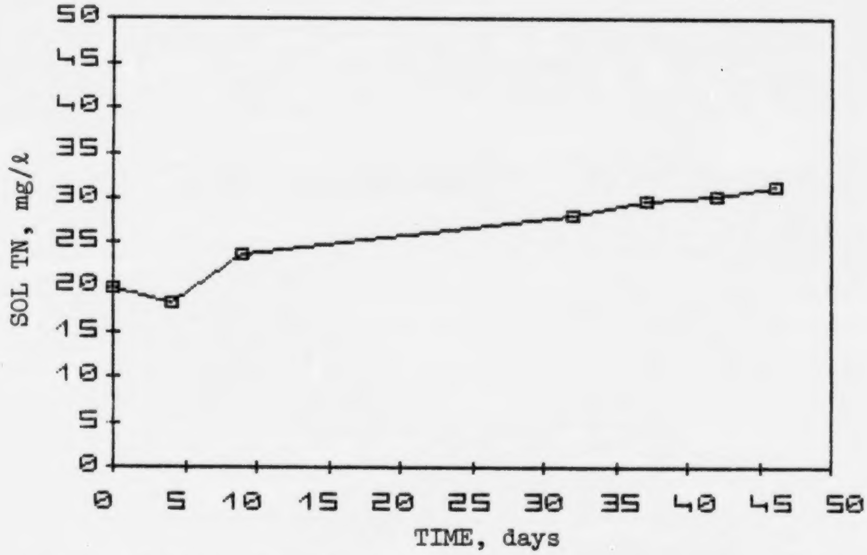

Figure C.126. Soluble total nitrogen concentration of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

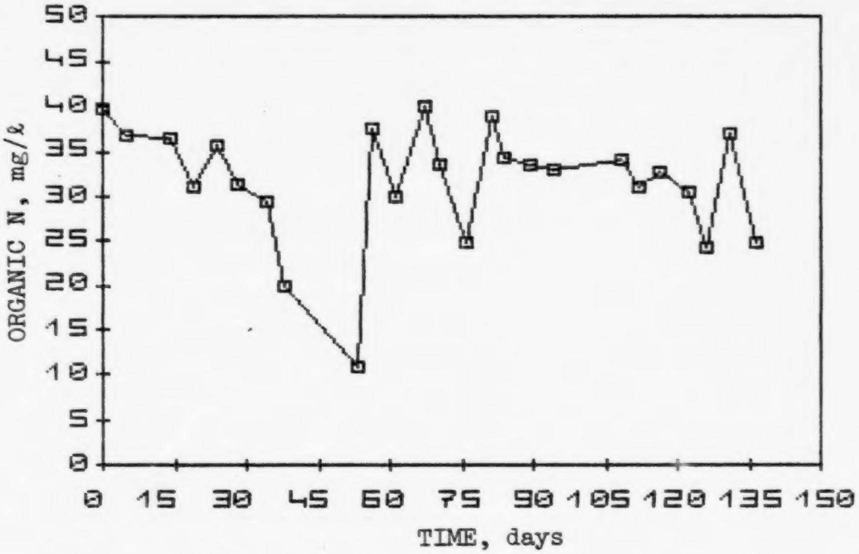

Figure C.127. Organic nitrogen concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

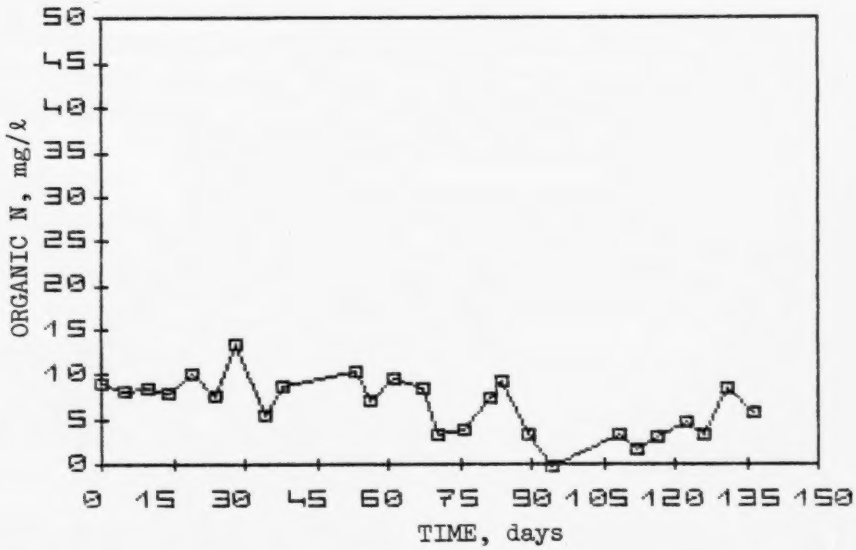

Figure C.128. Organic nitrogen concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

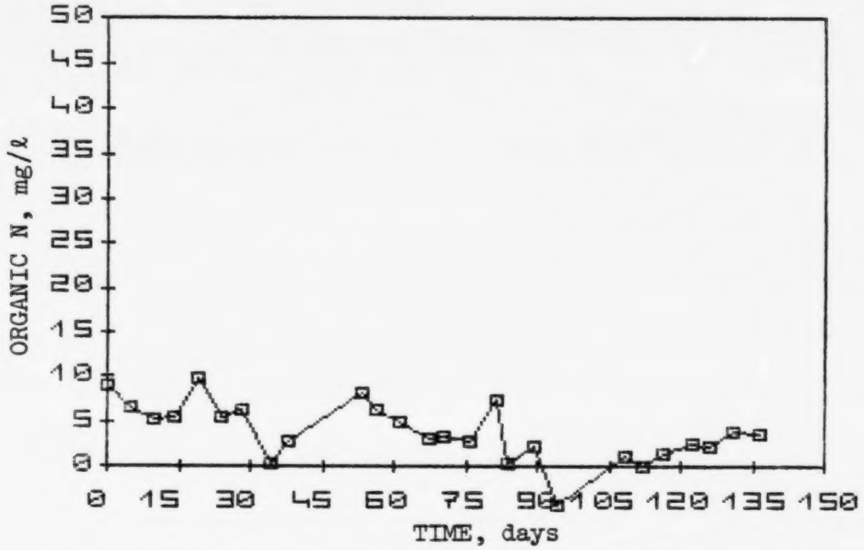

Figure C.129. Organic nitrogen concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

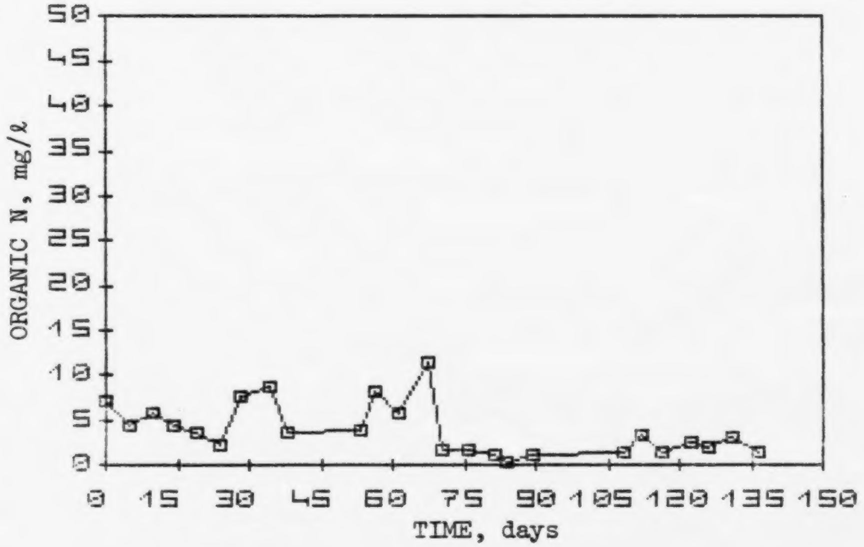

Figure C.130. Organic nitrogen concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

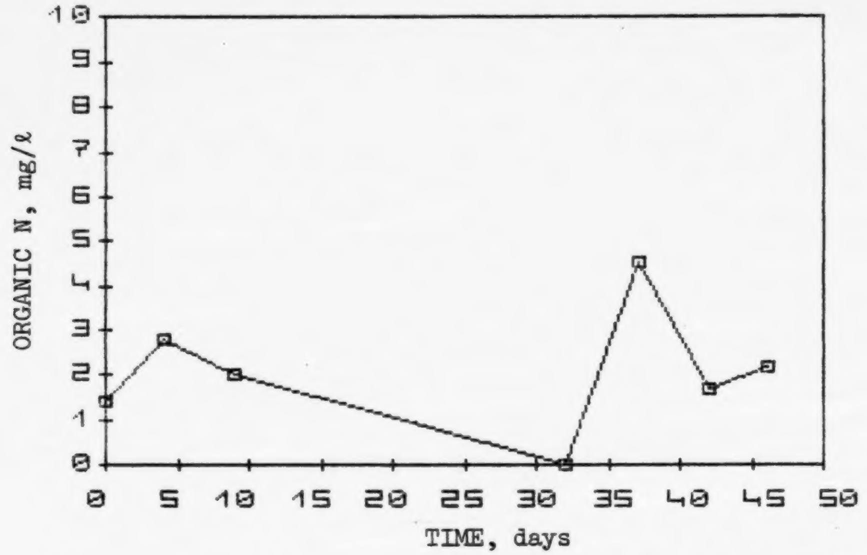

Figure C.131. Organic nitrogen concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

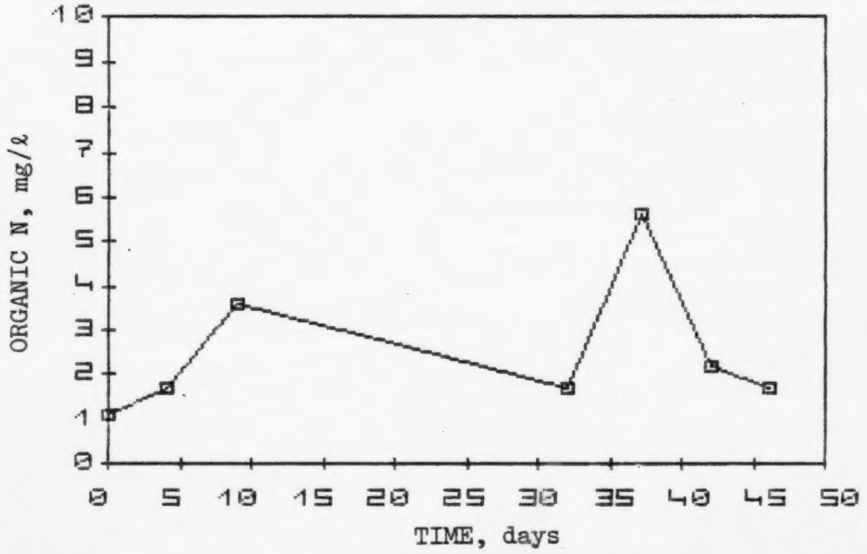

Figure C.132. Organic nitrogen concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

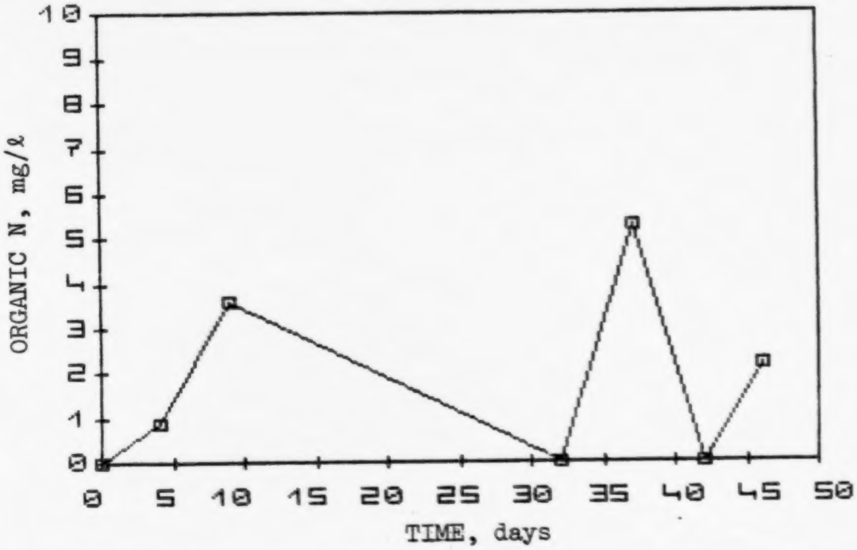

Figure C.133. Organic nitrogen concentration of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

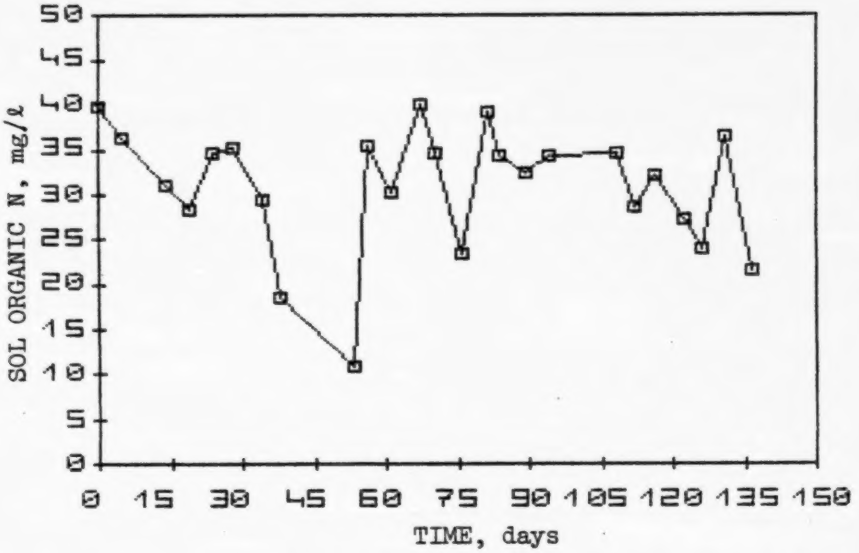

Figure C.134. Soluble organic nitrogen concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

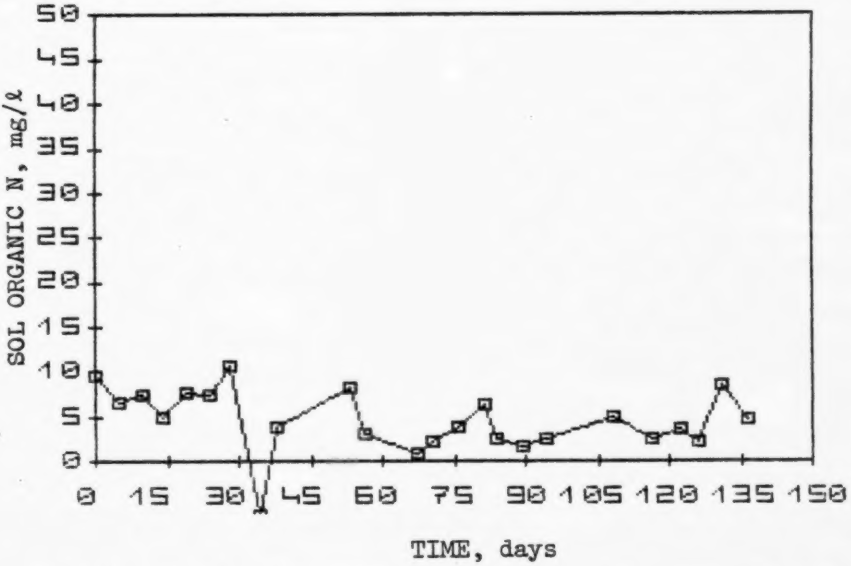

Figure C.135. Soluble organic nitrogen concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

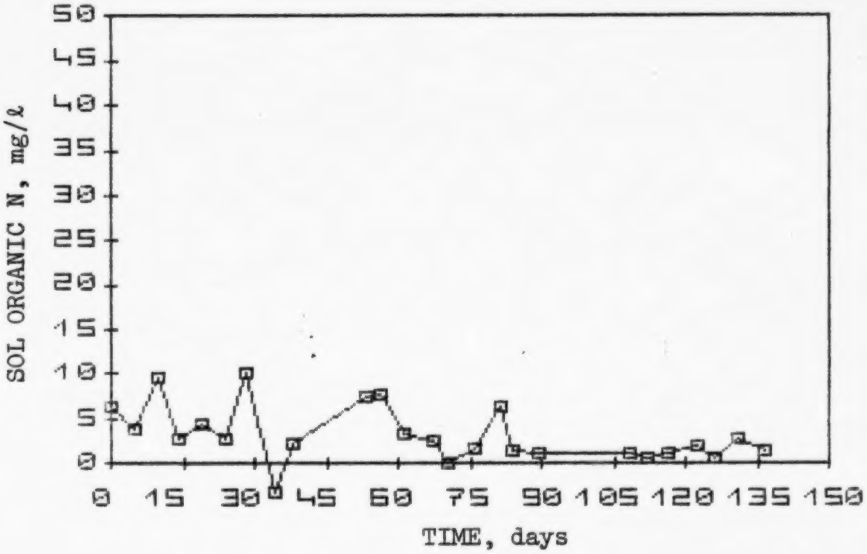

Figure C.136. Soluble organic nitrogen concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

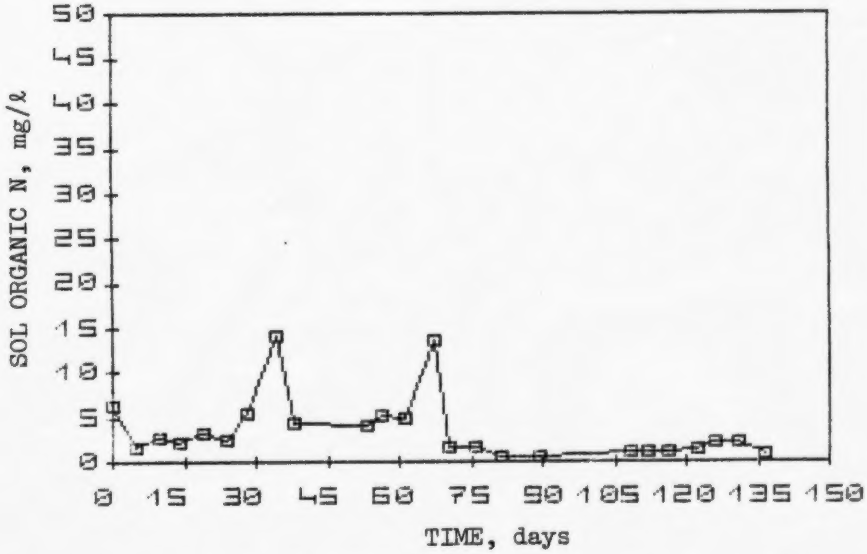

Figure C.137. Soluble organic nitrogen concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

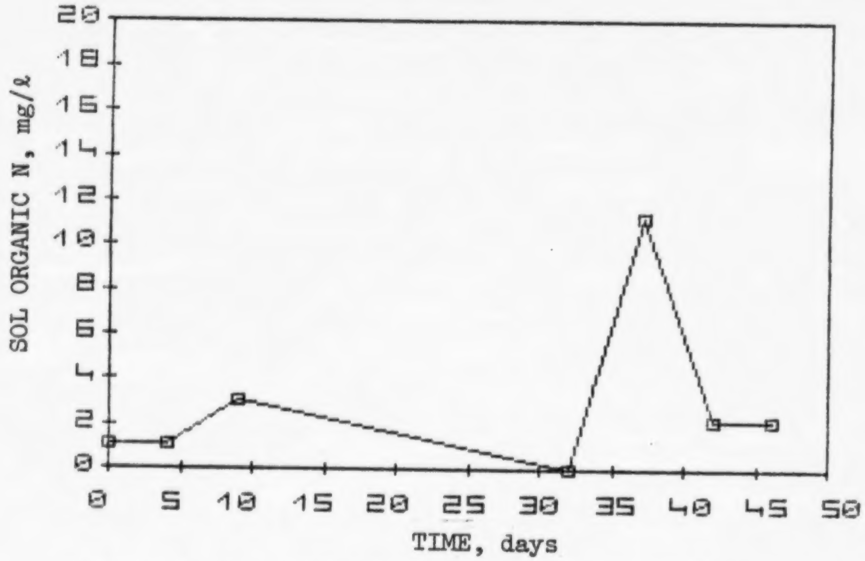

Figure C.138. Soluble organic nitrogen concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

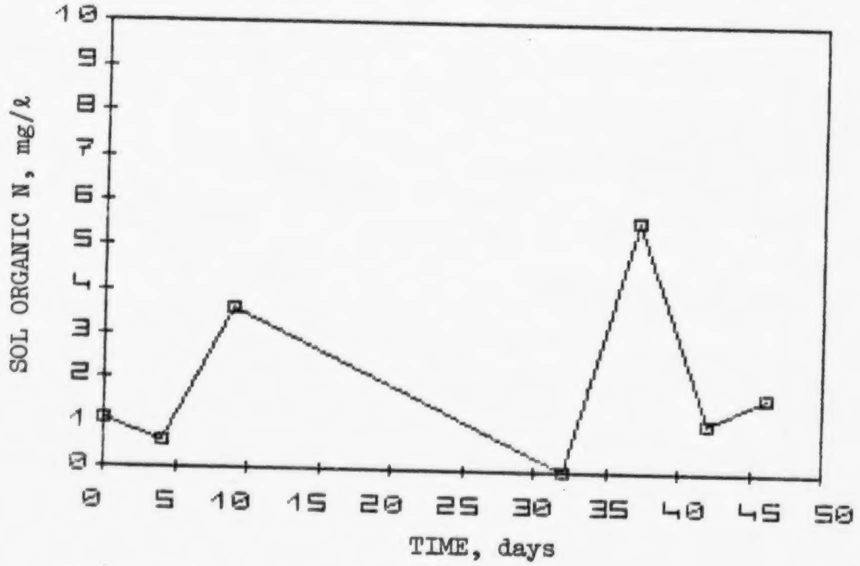

Figure C.139. Soluble organic nitrogen concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

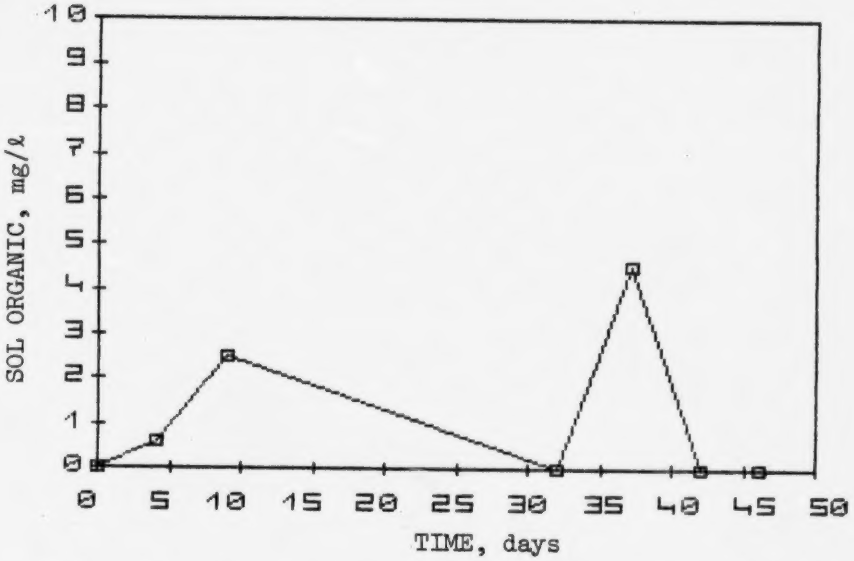

Figure C.140. Soluble organic nitrogen concentration of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

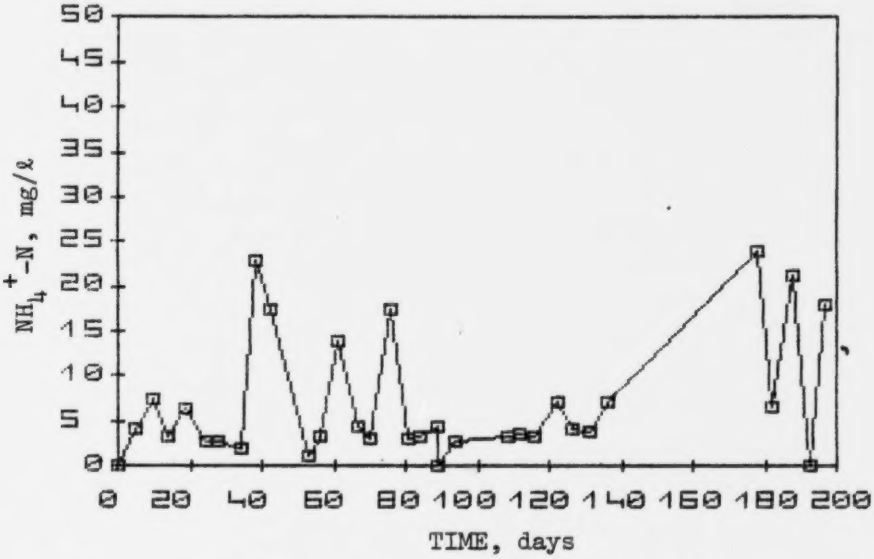

Figure C.141. Ammonia nitrogen concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

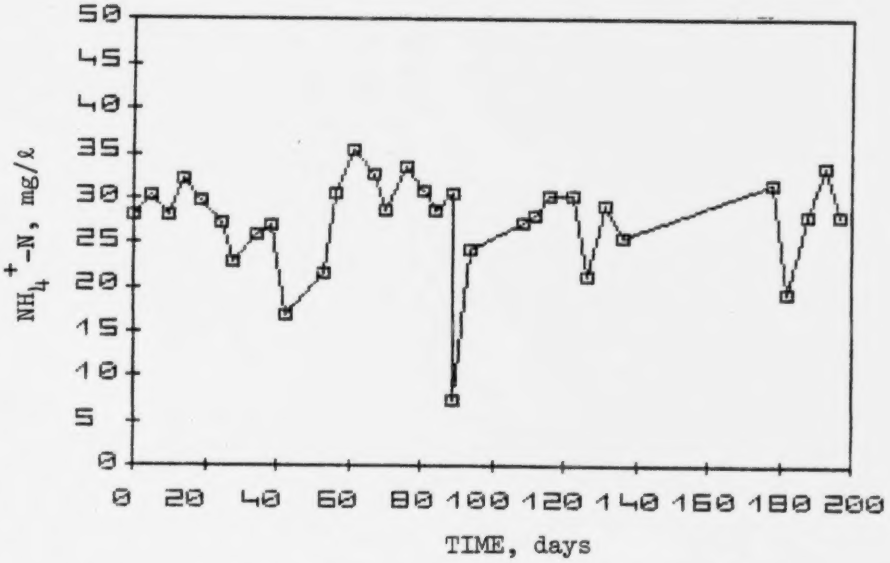

Figure C.142. Ammonia nitrogen concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

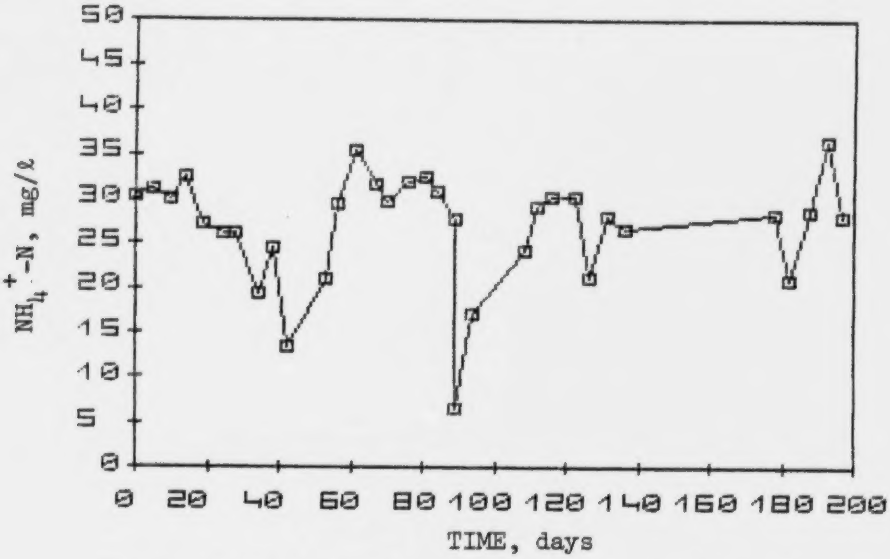

Figure C.143. Ammonia nitrogen concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

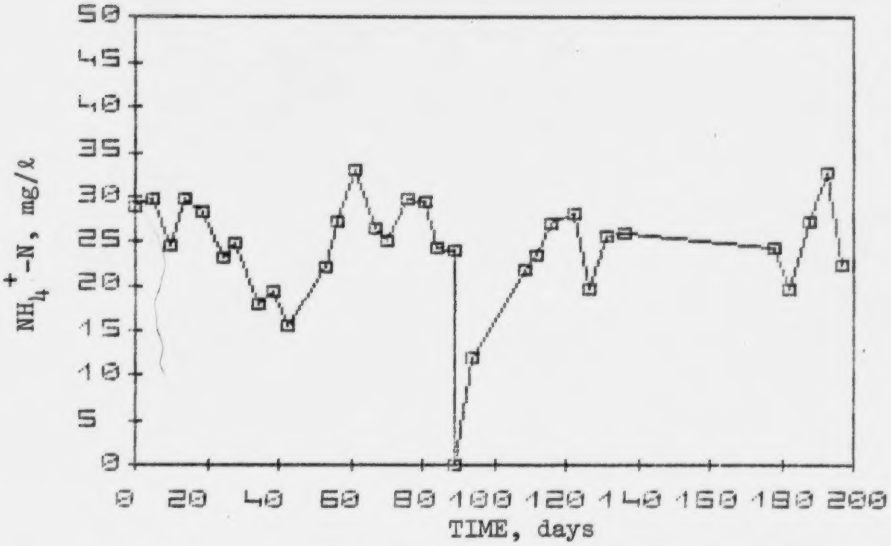

Figure C.144. Ammonia nitrogen concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

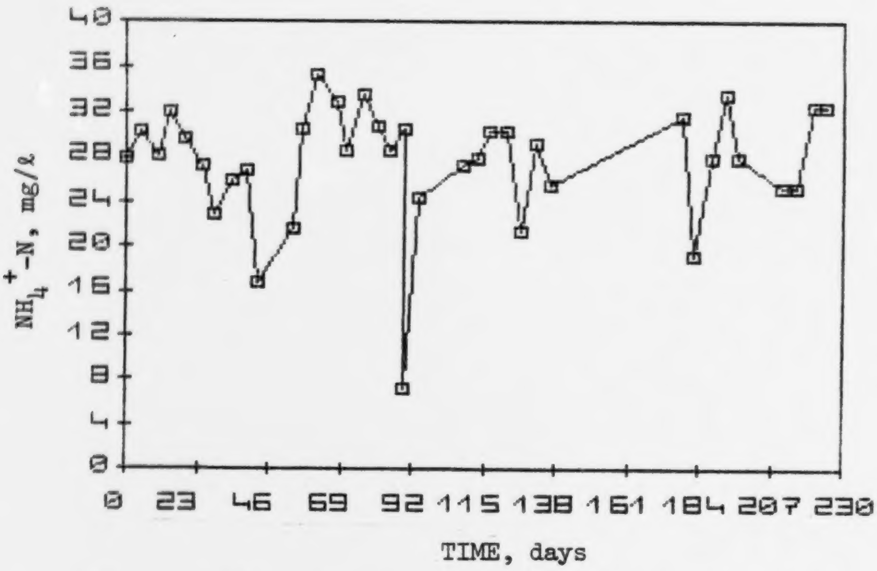

Figure C.145. Ammonia nitrogen concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

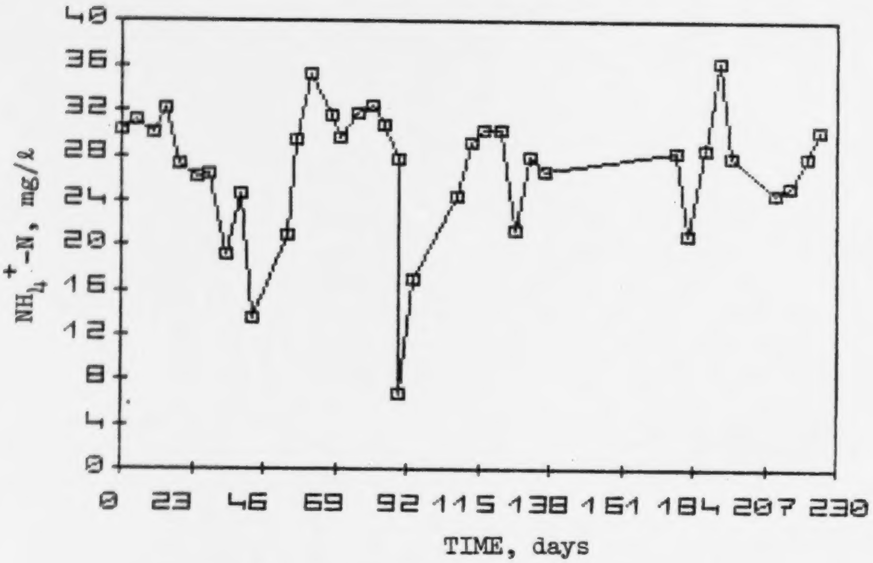

Figure C.146. Ammonia nitrogen concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

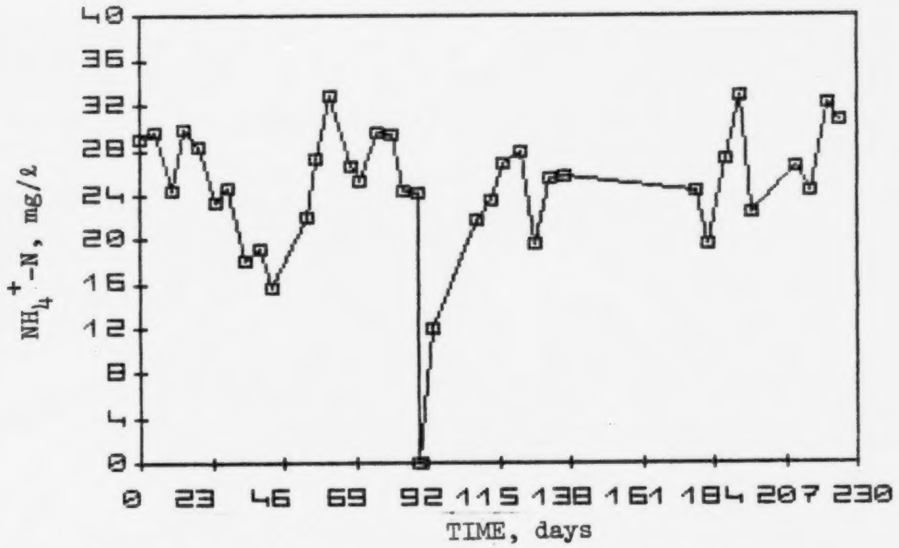

Figure C.147. Ammonia nitrogen concentration of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

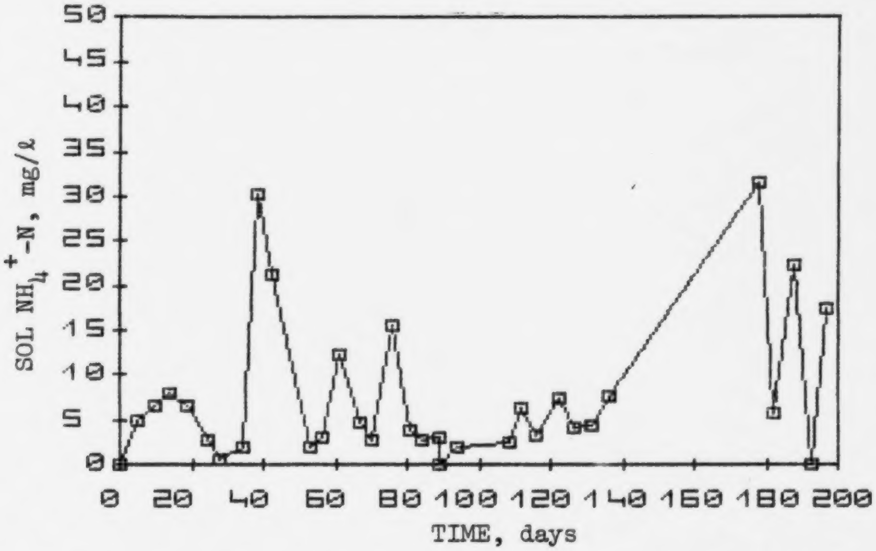

Figure C.148. Soluble ammonia nitrogen concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

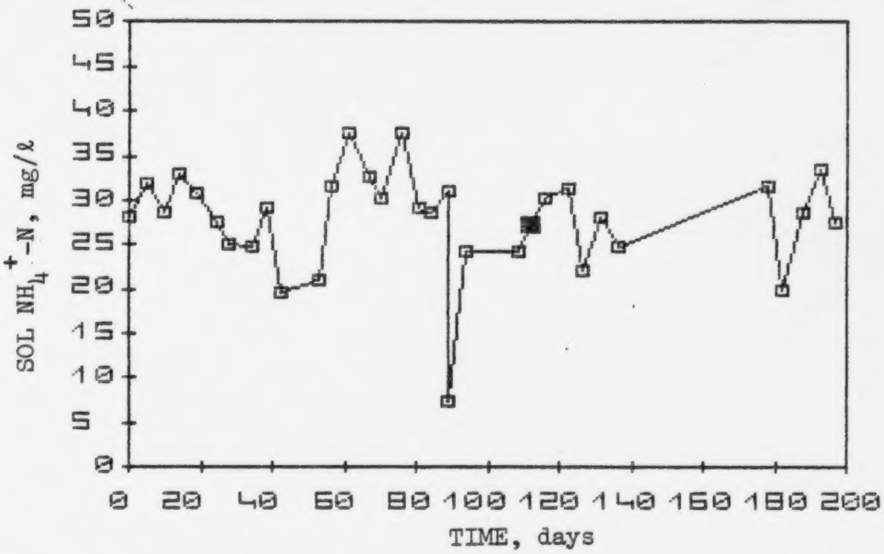

Figure C.149. Soluble ammonia nitrogen concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

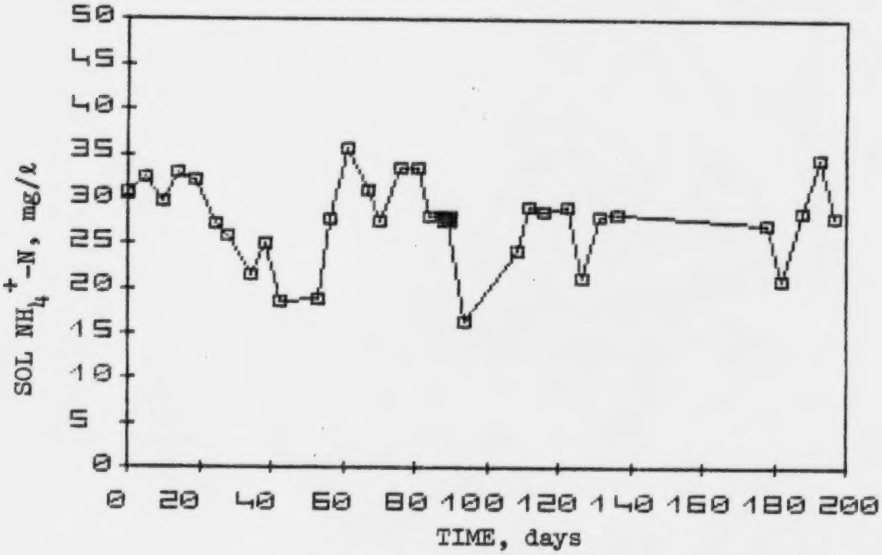

Figure C.150. Soluble ammonia nitrogen concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

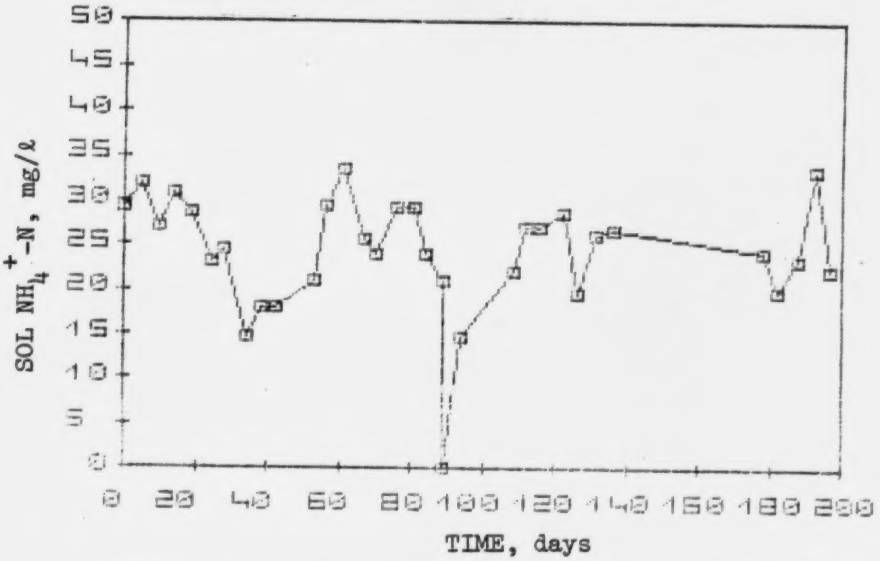

Figure C.151. Soluble ammonia nitrogen concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

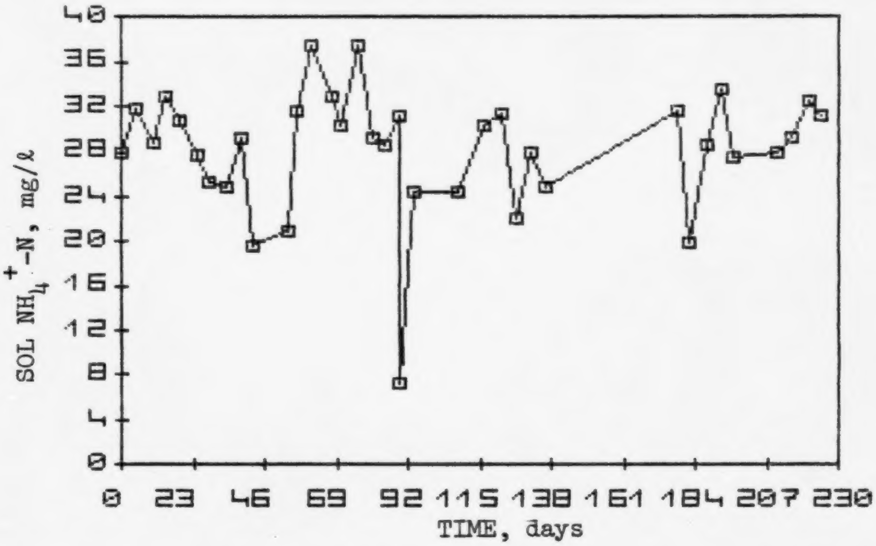

Figure C.152. Soluble ammonia nitrogen concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

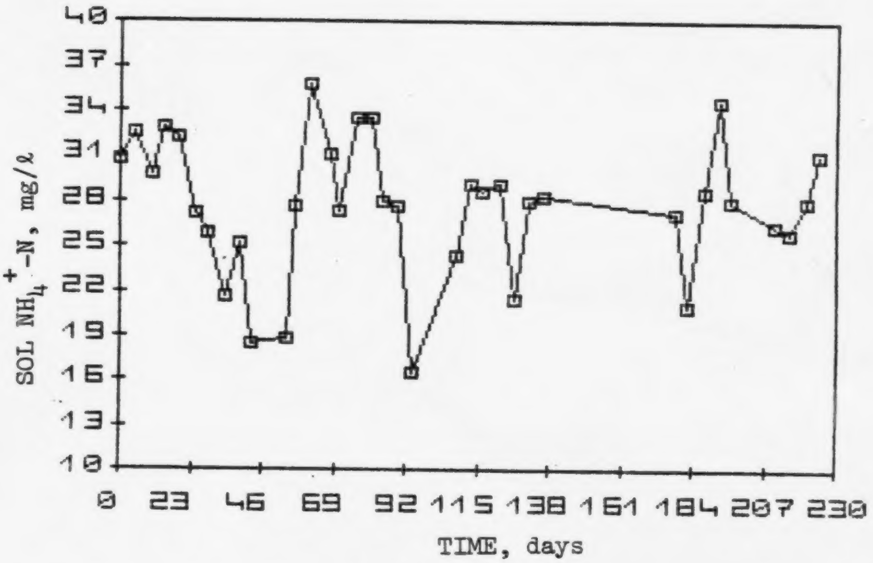

Figure C.153. Soluble ammonia nitrogen concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

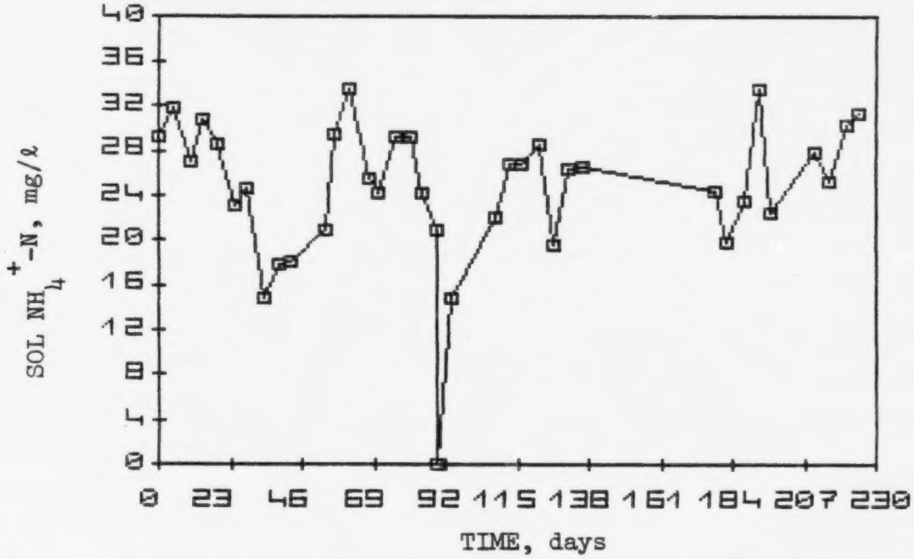

Figure C.154. Soluble ammonia nitrogen concentration of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

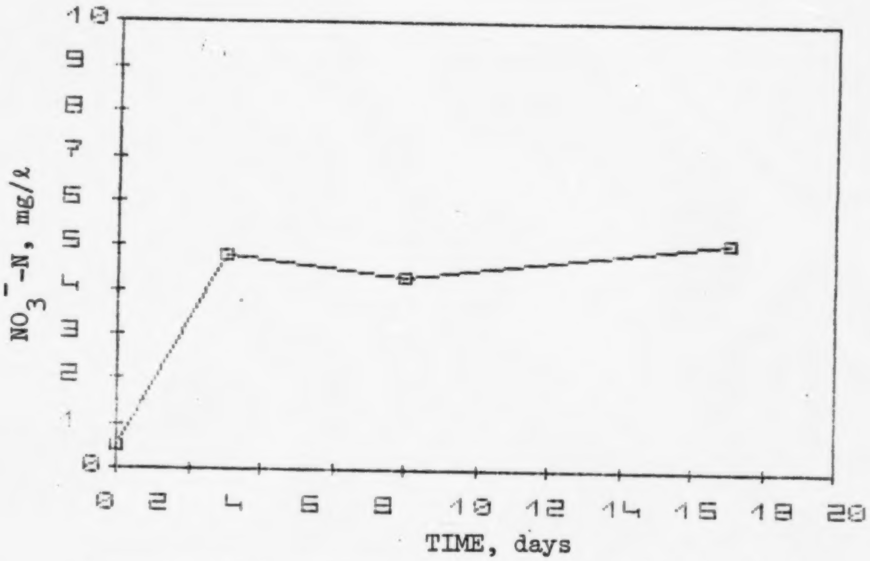

Figure C.155. Nitrate nitrogen concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was May 13, 1980.

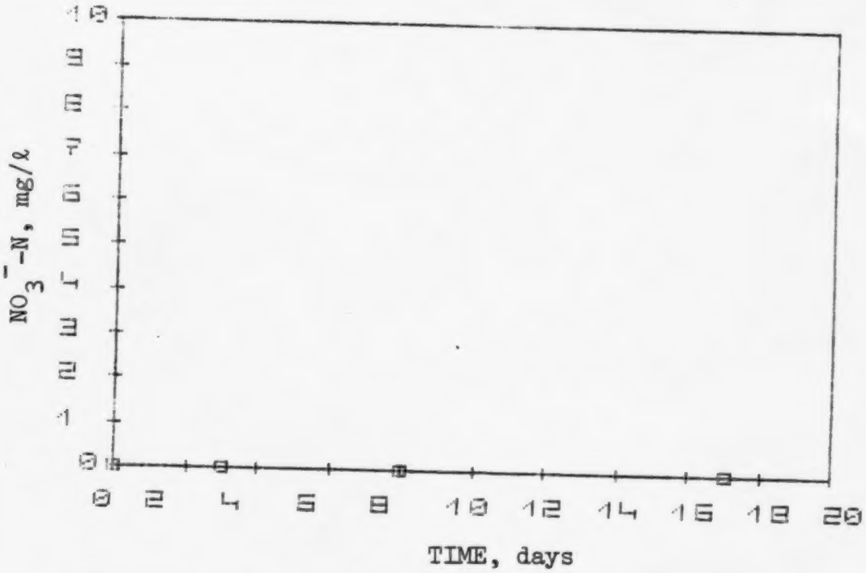

Figure C.156. Nitrate nitrogen concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was May 13, 1980.

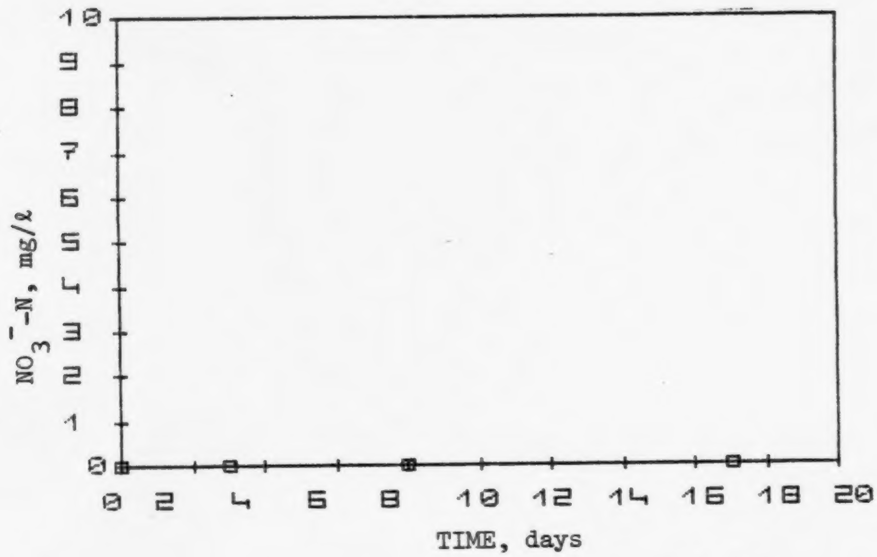

Figure C.157. Nitrate nitrogen concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was May 13, 1980.

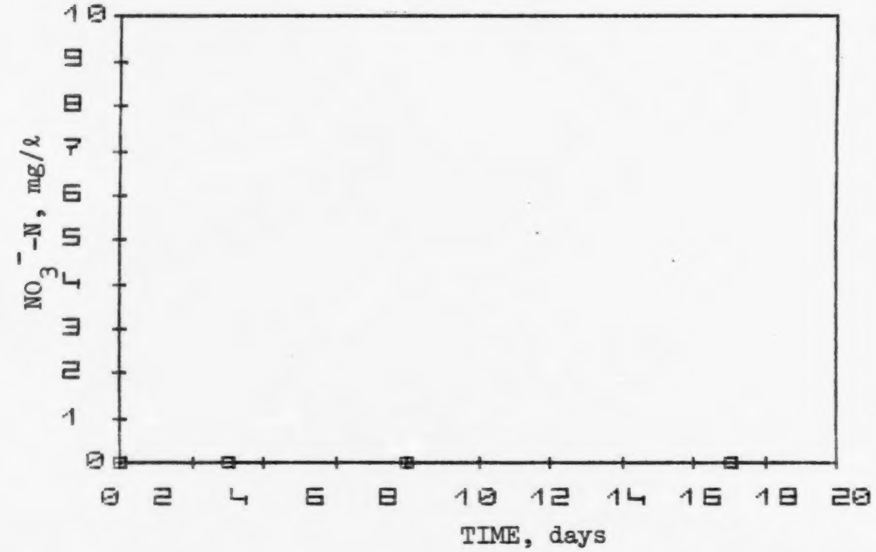

Figure C.158. Nitrate nitrogen concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was May 13, 1980.

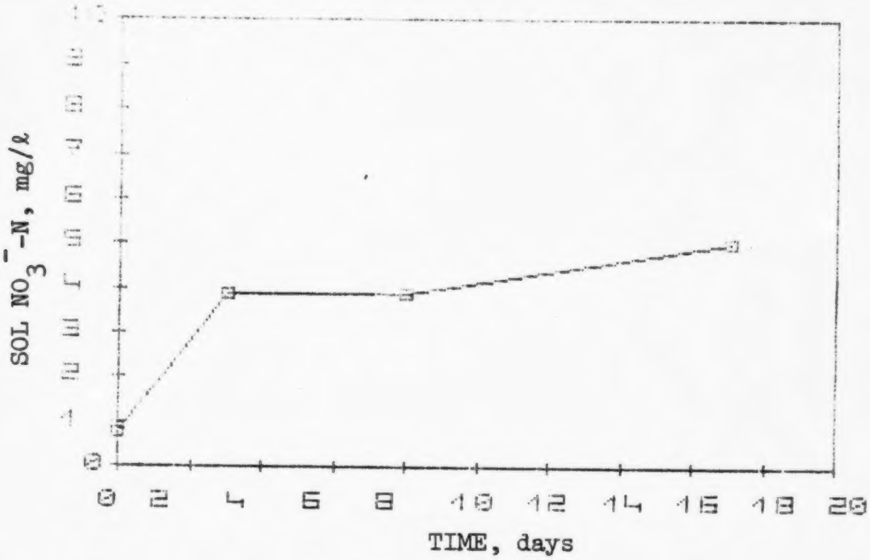

Figure C.159. Soluble nitrate nitrogen concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was May 13, 1980.

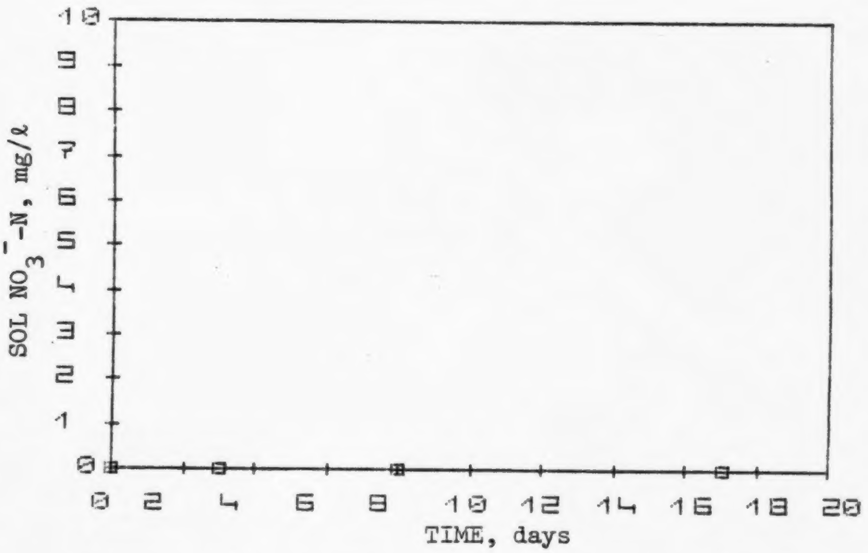

Figure C.160. Soluble nitrate nitrogen concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was May 13, 1980.

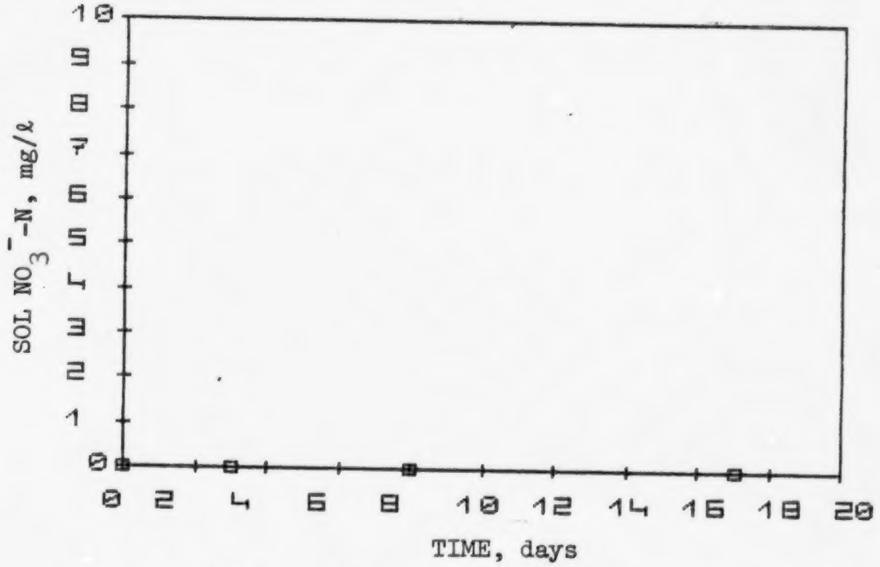

Figure C.161. Soluble nitrate nitrogen concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was May 13, 1980.

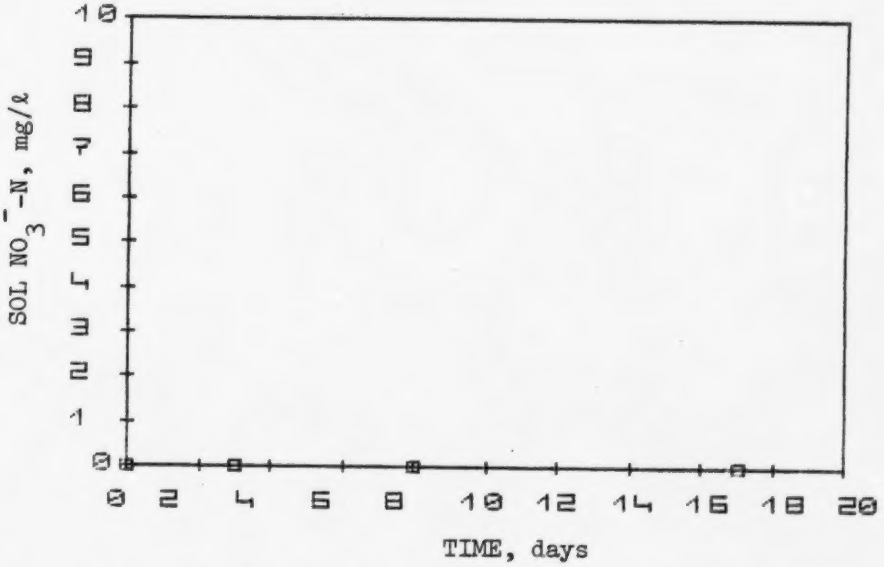

Figure C.162. Soluble nitrate nitrogen concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was May 13, 1980.

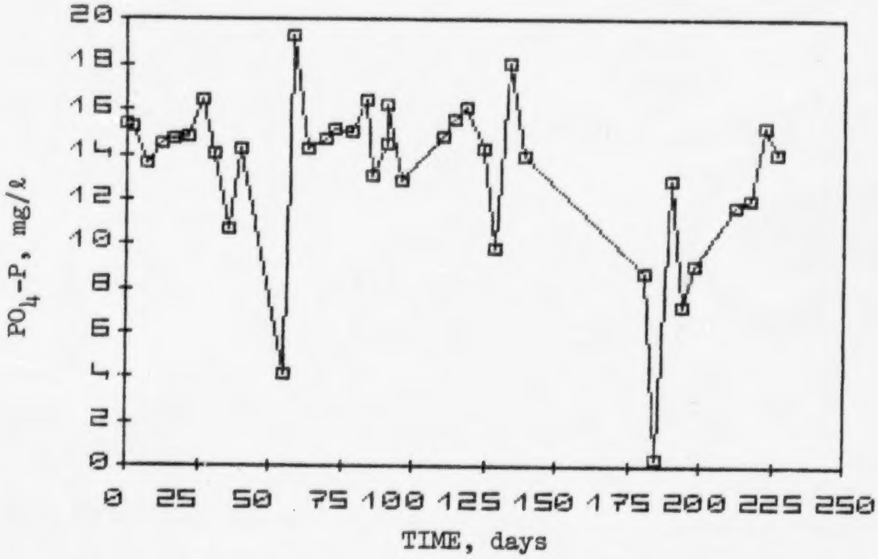

Figure C.163. Orthophosphate phosphorus concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

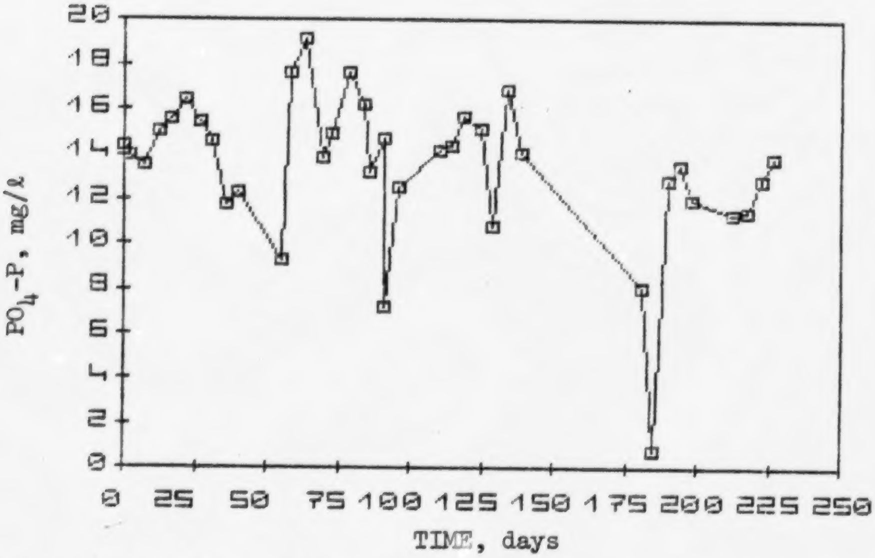

Figure C.164. Orthophosphate phosphorus concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

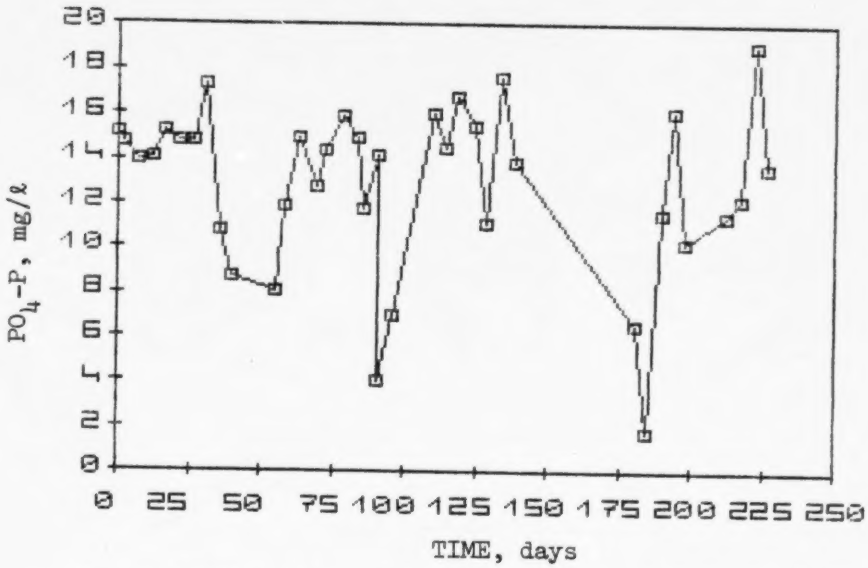

Figure C.165. Orthophosphate phosphorus concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

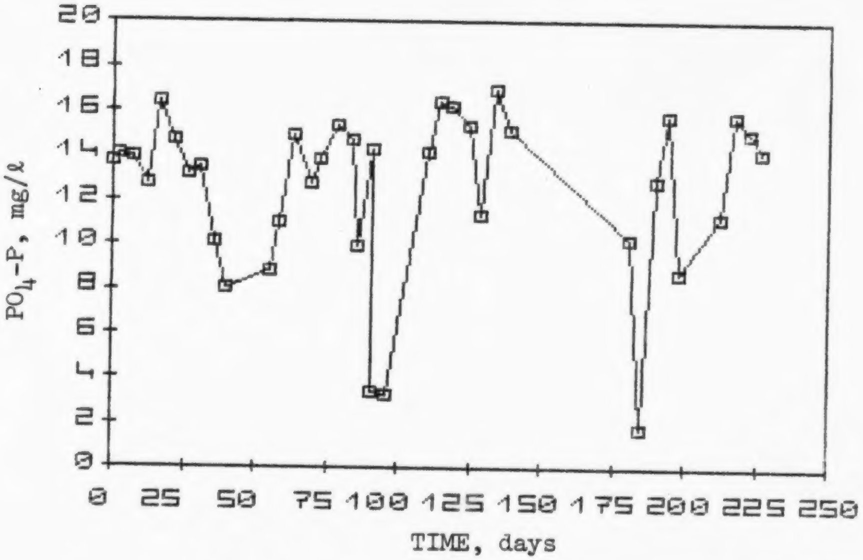

Figure C.166. Orthophosphate phosphorus concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

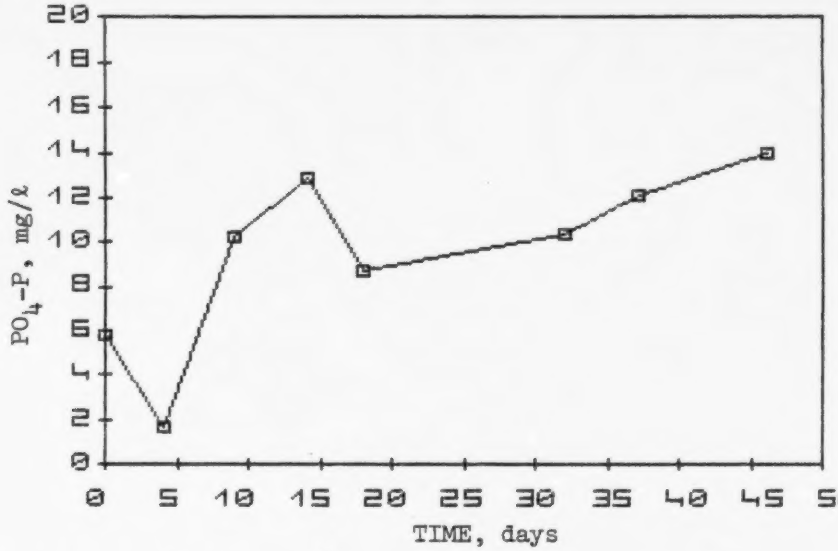

Figure C.167. Orthophosphate phosphorus concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

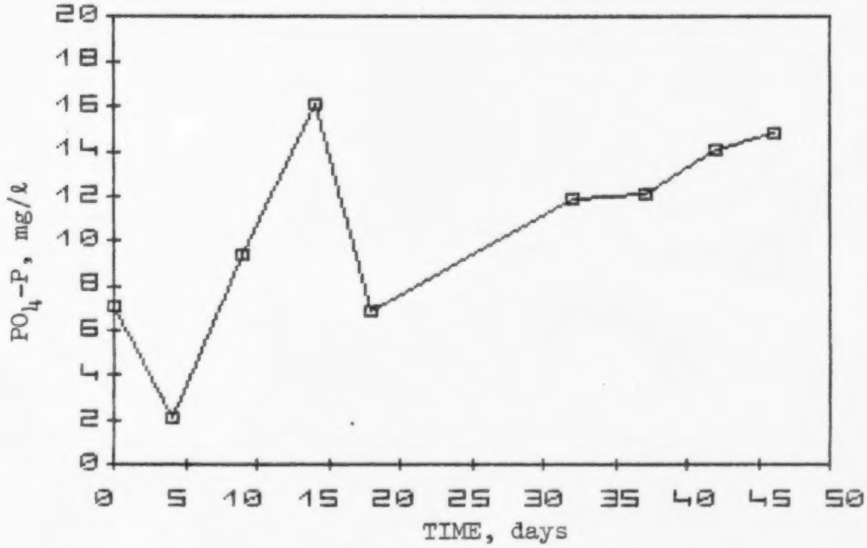

Figure C.168. Orthophosphate phosphorus concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

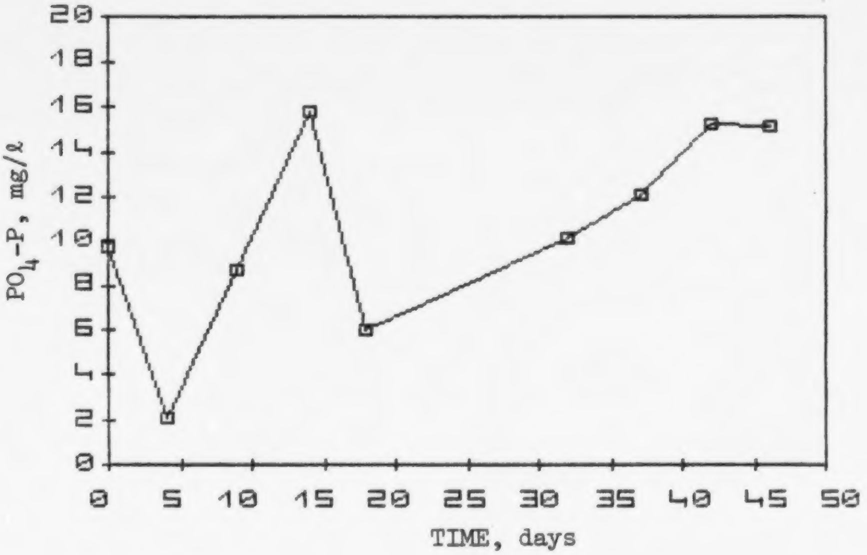

Figure C.169. Orthophosphate phosphorus concentration of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

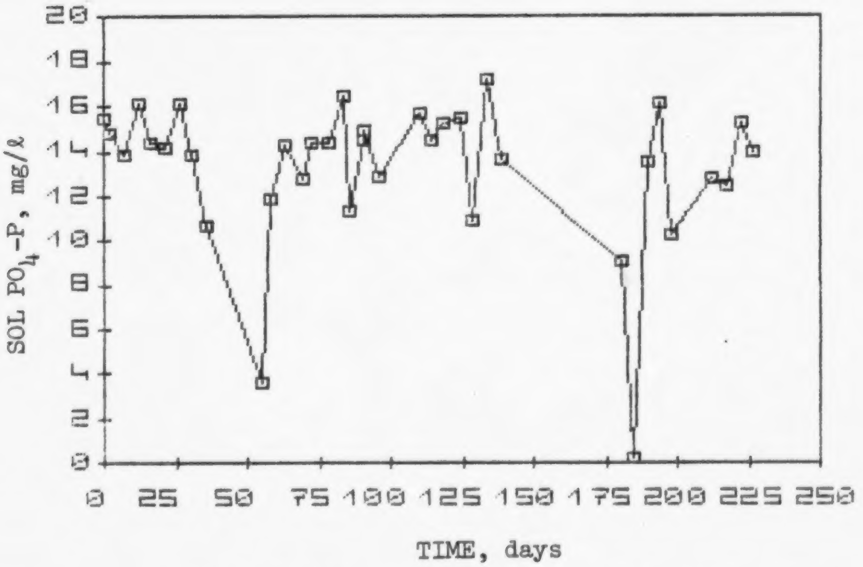

Figure C.170. Soluble orthophosphate phosphorus concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

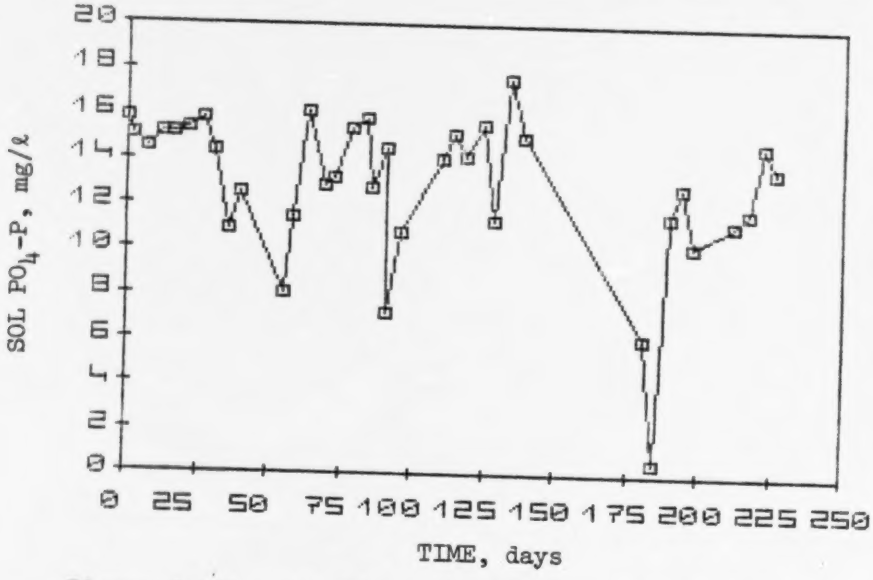

Figure C.171. Soluble orthophosphate phosphorus concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT unit in Phase 1. First day of analysis was March 19, 1980.

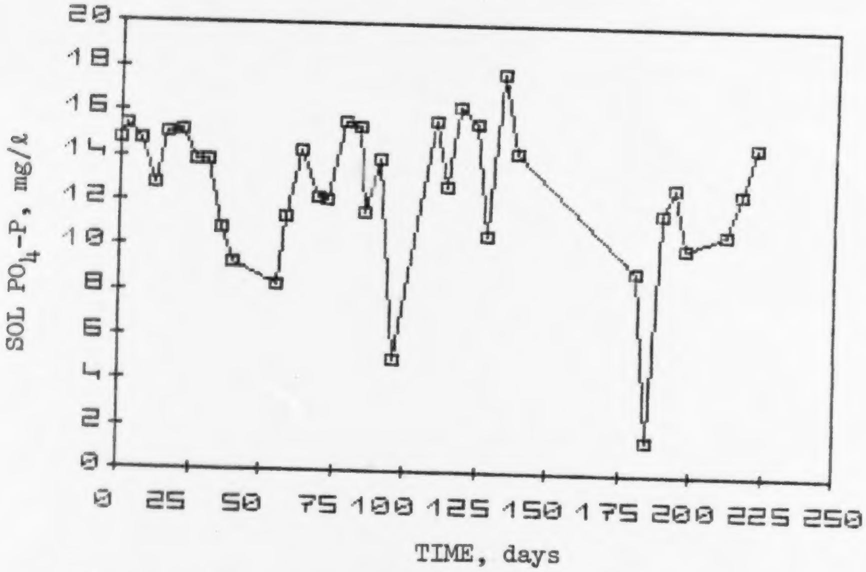

Figure C.172. Soluble orthophosphate phosphorus concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

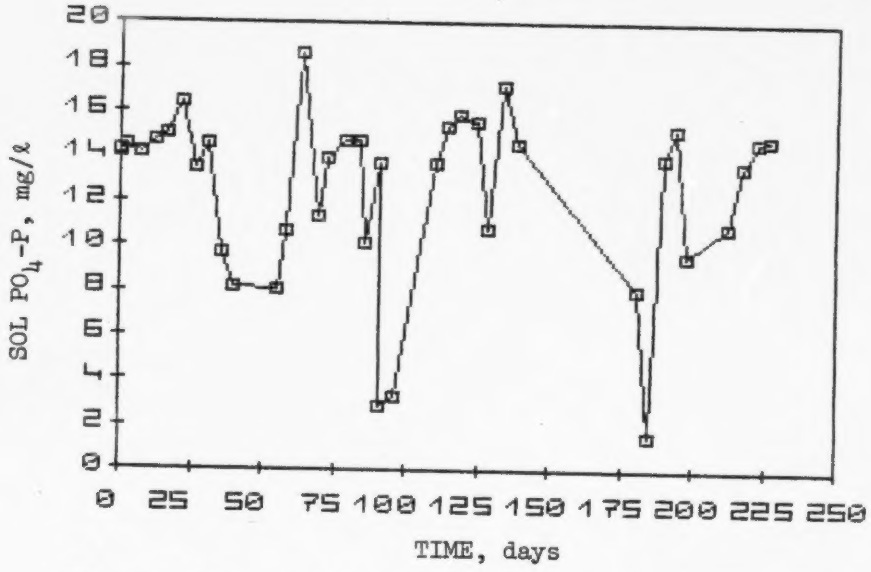

Figure C.173. Soluble orthophosphate phosphorus concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

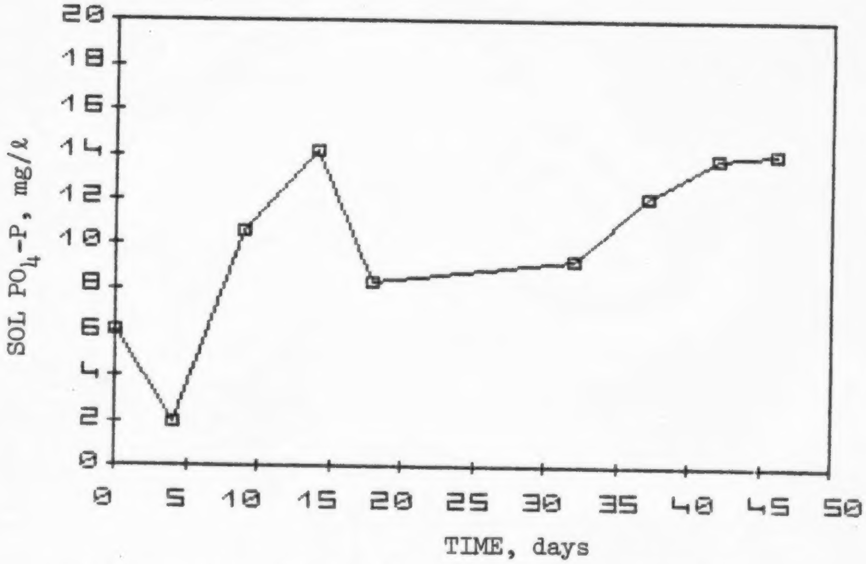

Figure C.174. Soluble orthophosphate phosphorus concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

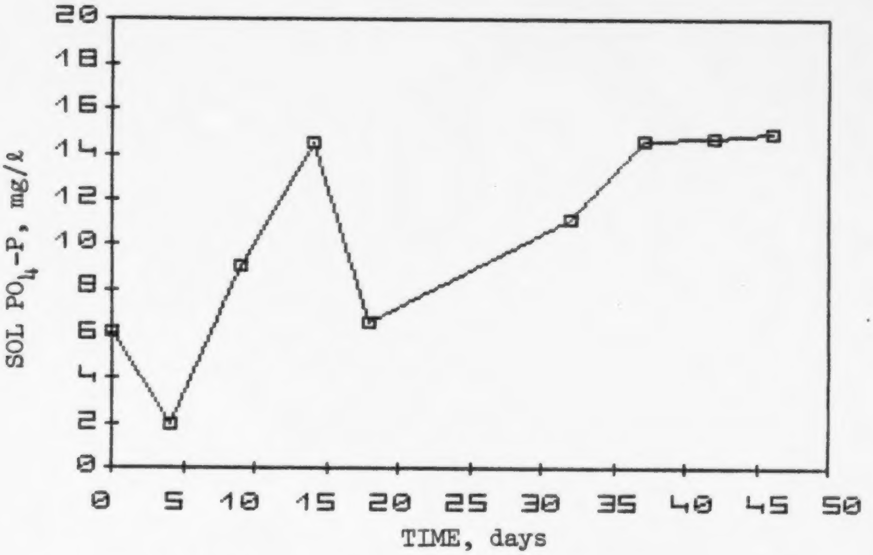

Figure C.175. Soluble orthophosphate phosphorus concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

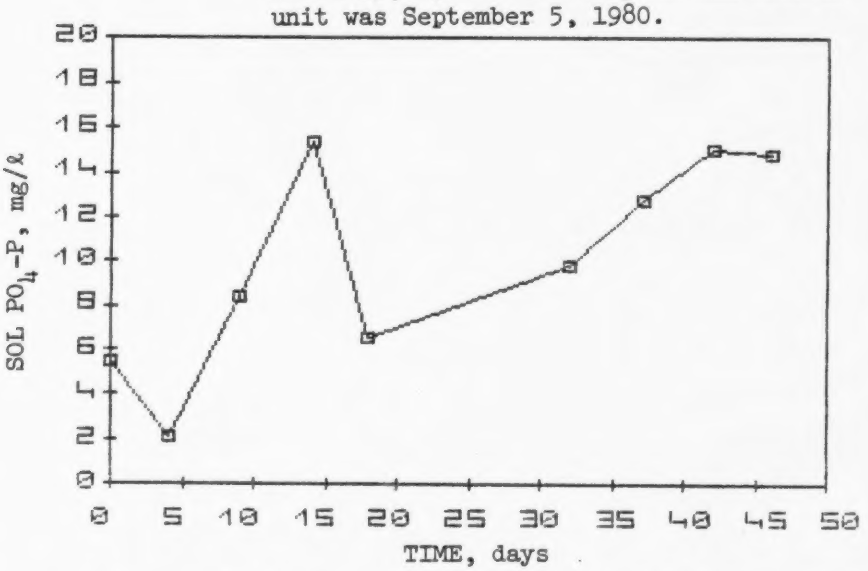

Figure C.176. Soluble orthophosphate phosphorus concentration of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

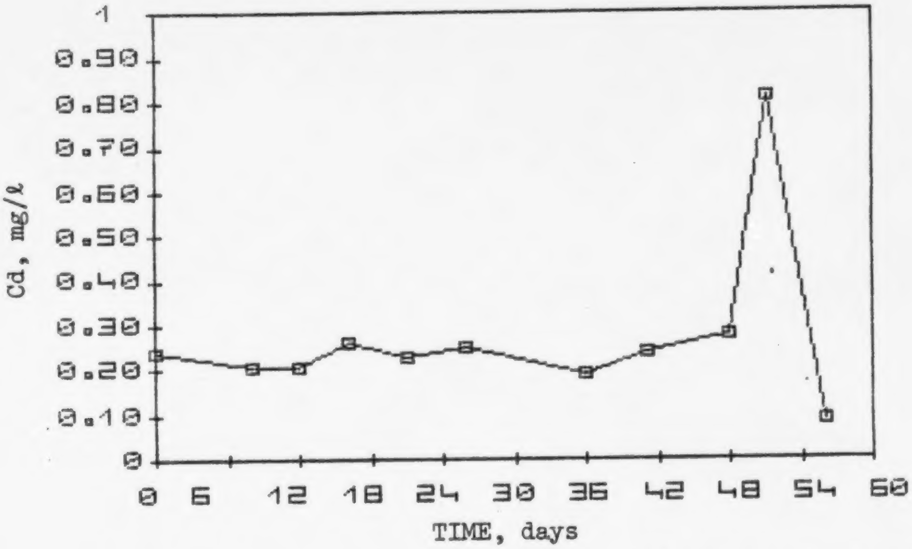

Figure C.177. Cadmium concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

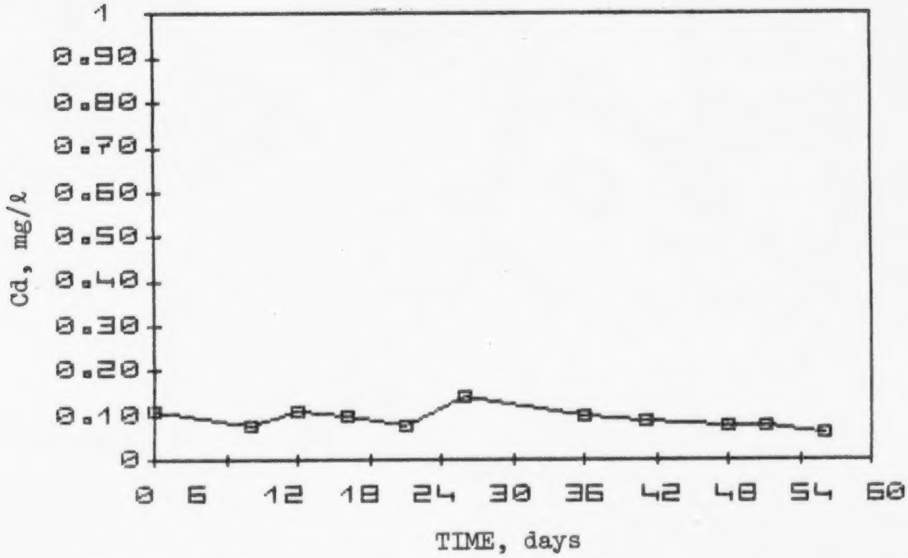

Figure C.178. Cadmium concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

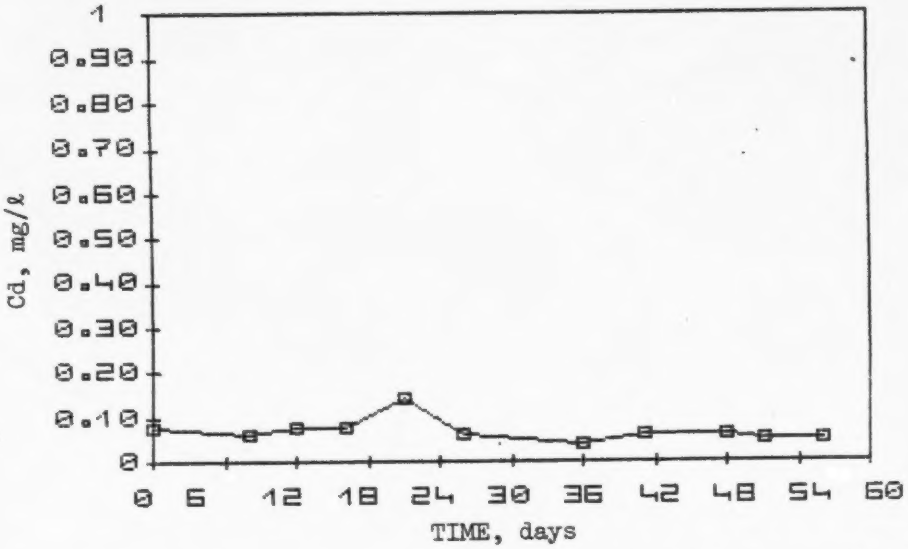

Figure C.179. Cadmium concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

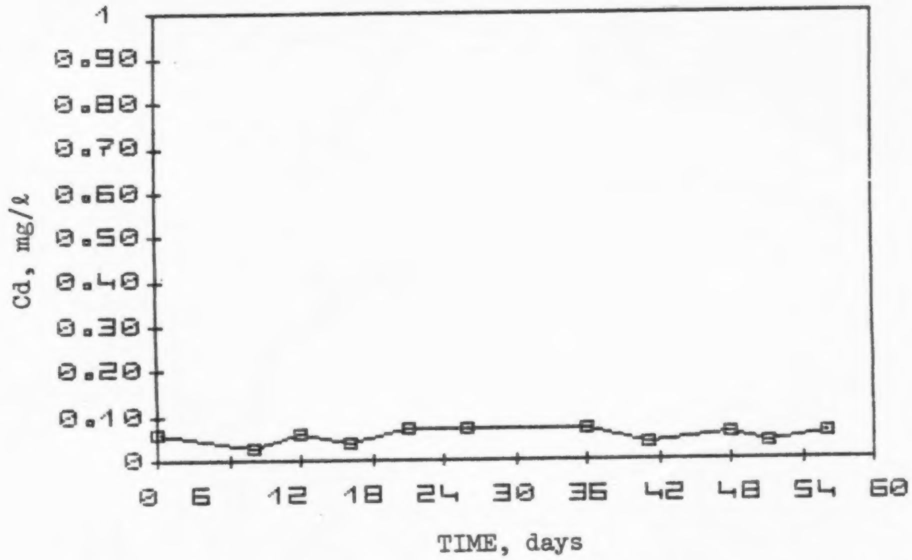

Figure C.180. Cadmium concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

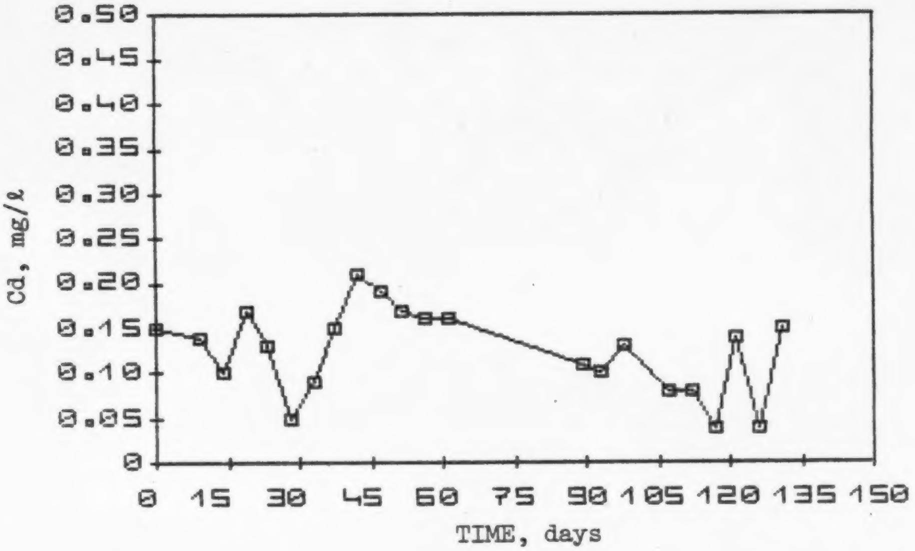

Figure C.181. Cadmium concentration of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

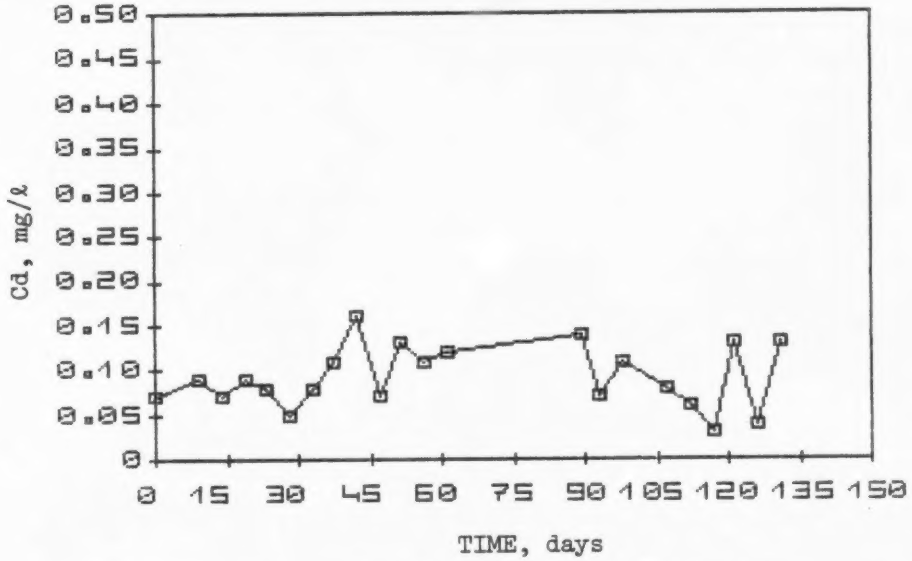

Figure C.182. Cadmium concentration of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

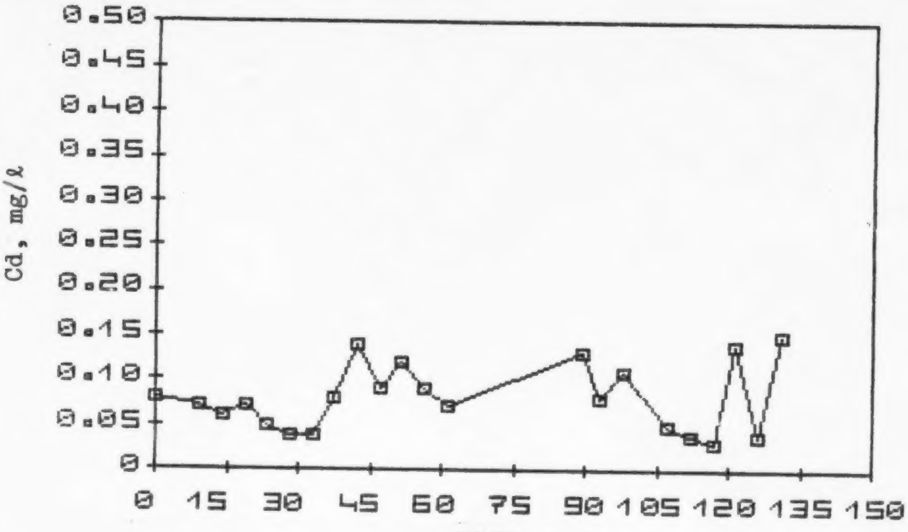

Figure C.183. Cadmium concentration of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

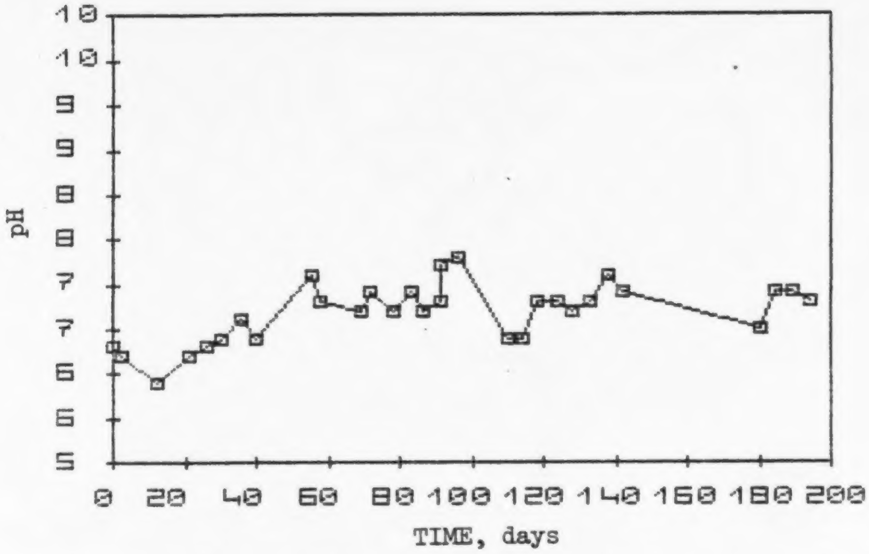

Figure C.184. pH of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

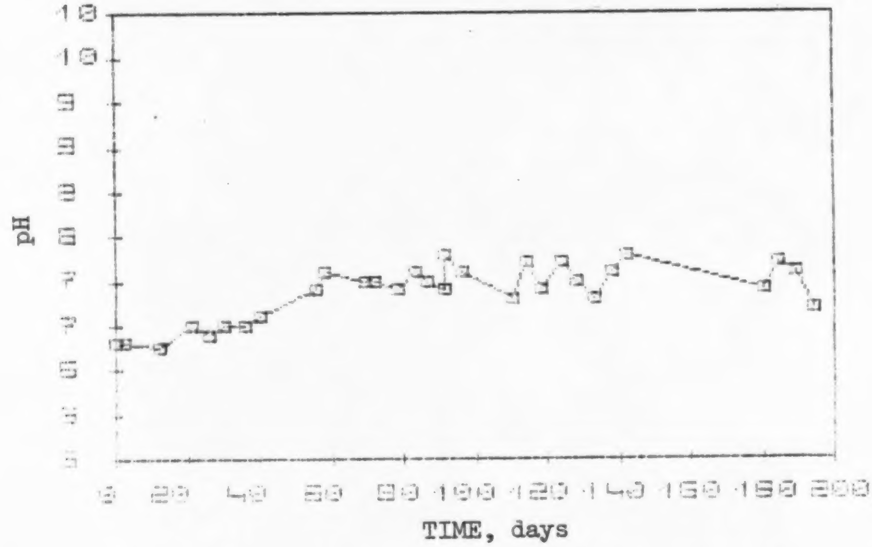

Figure C.185. pH of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

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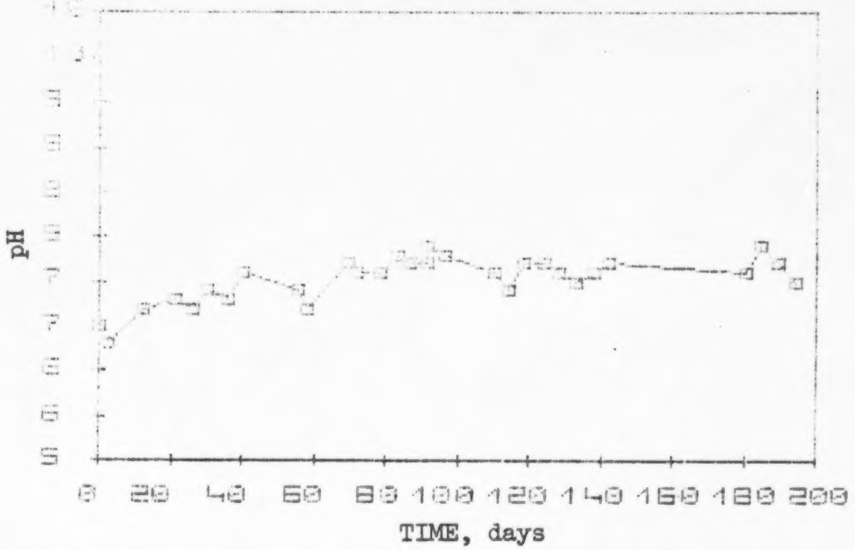

Figure C.186. pH of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

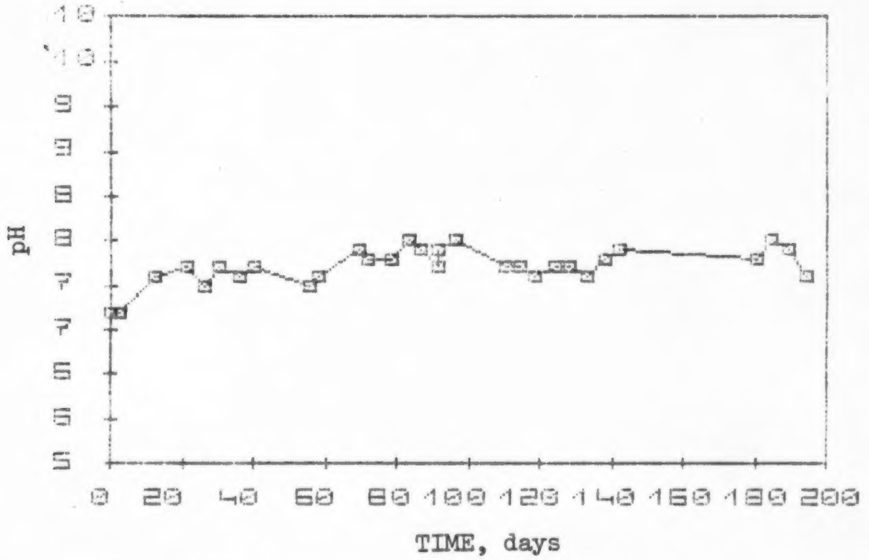

Figure C.187. pH of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

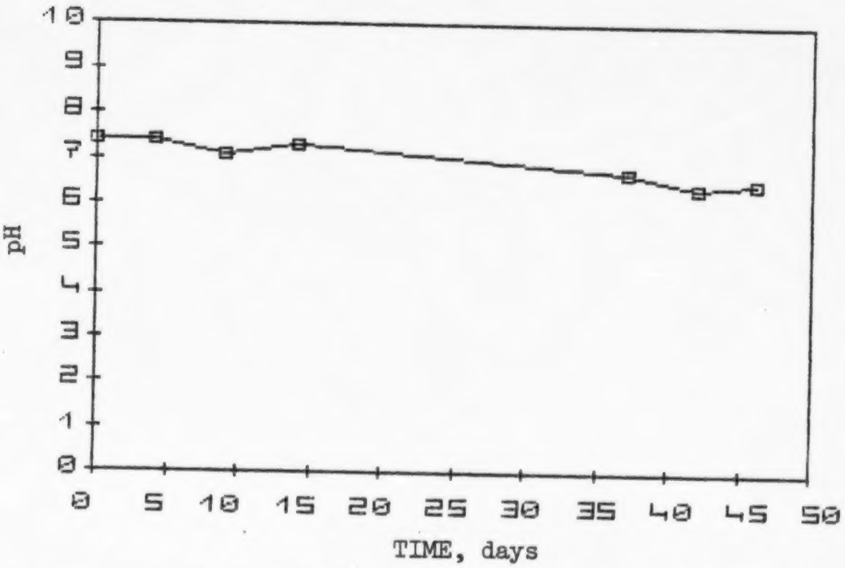

Figure C.188. pH of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

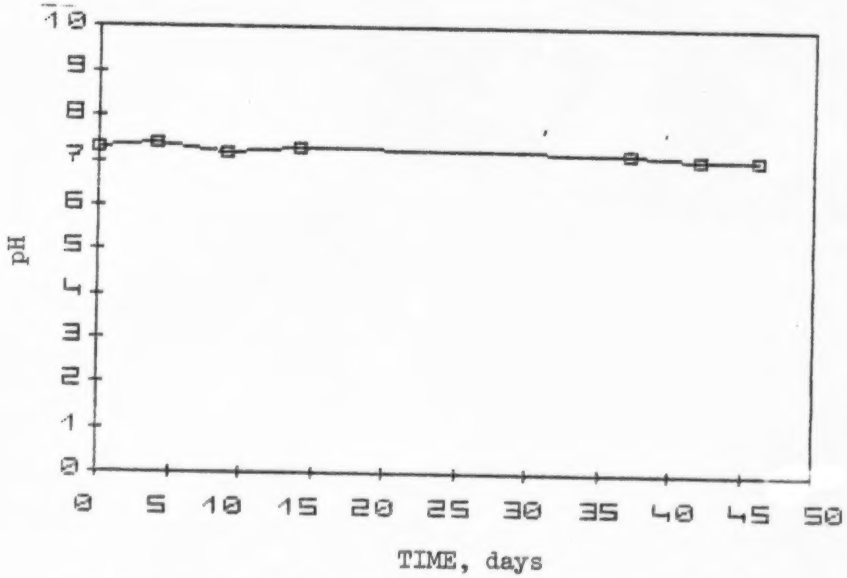

Figure C.189. pH of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

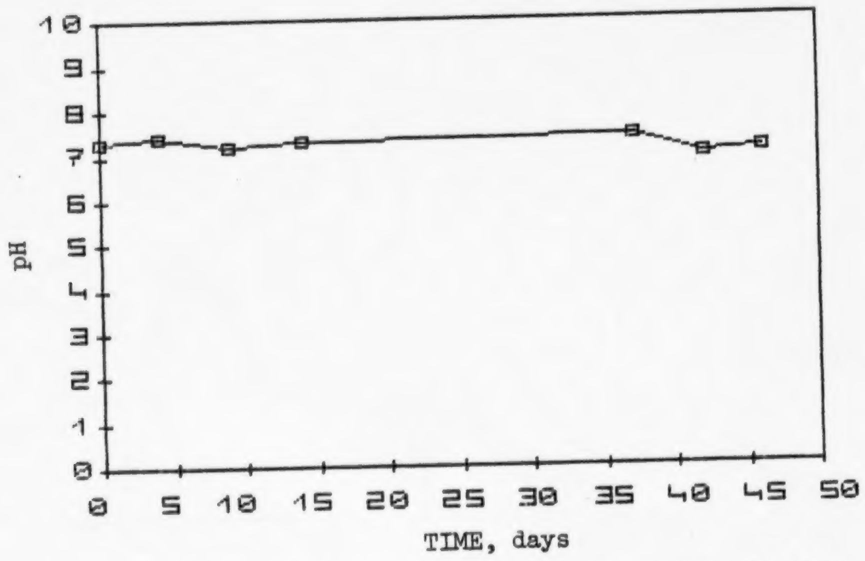

Figure C.190. pH of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

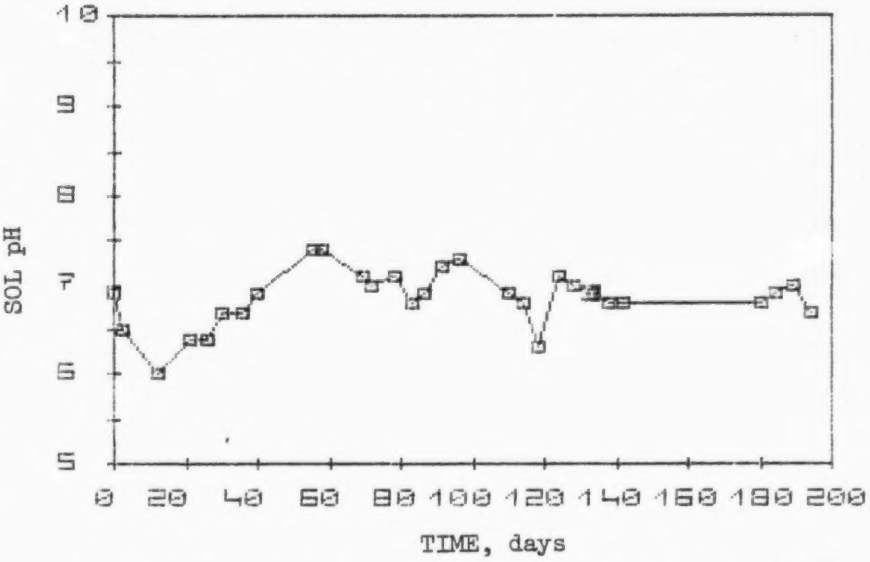

Figure C.191. Soluble pH of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

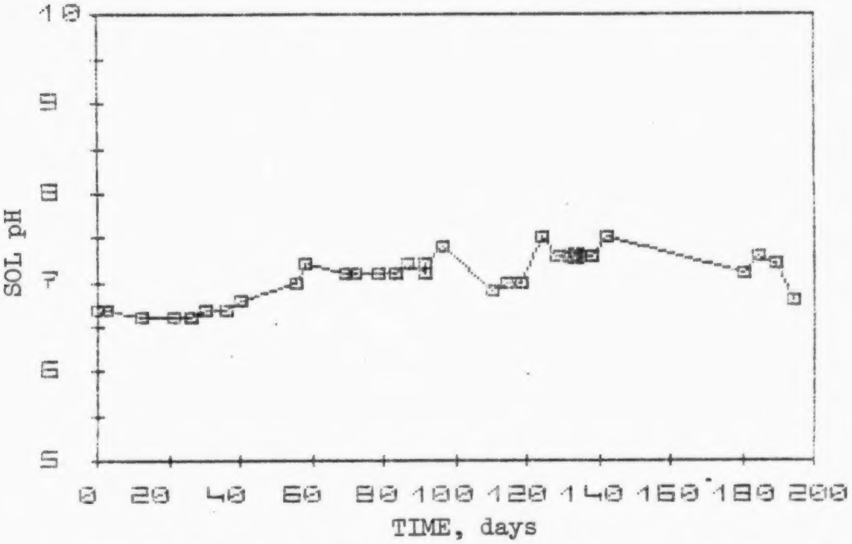

Figure C.192. Soluble pH of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

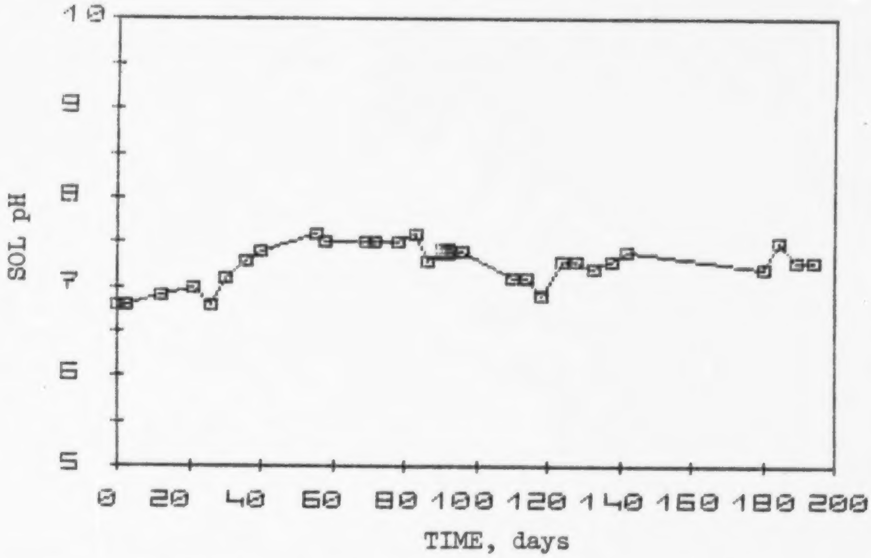

Figure C.193. Soluble pH of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

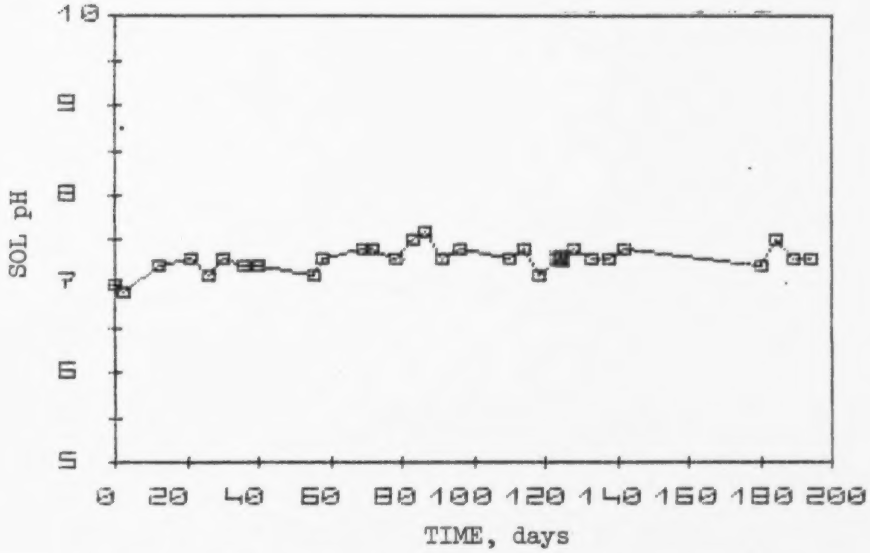

Figure C.194. Soluble pH of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

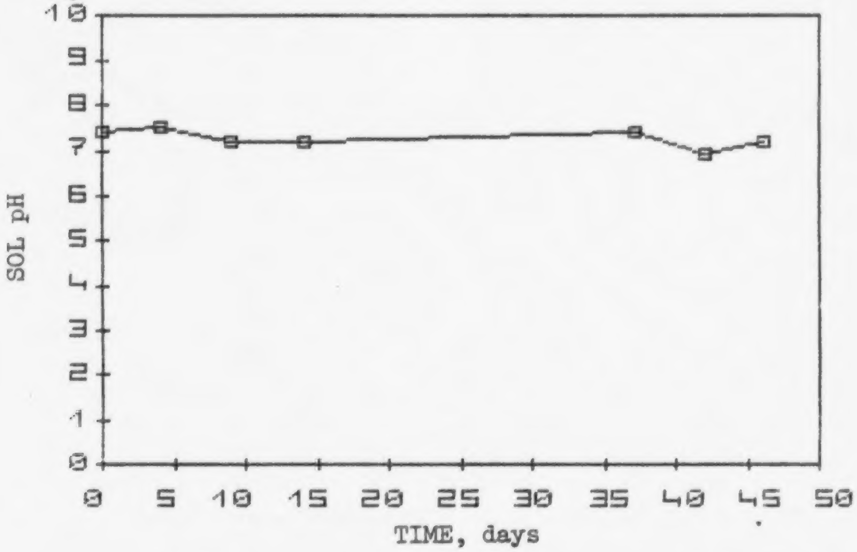

Figure C.195. Soluble pH of effluent synthetic sewage at Point A in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

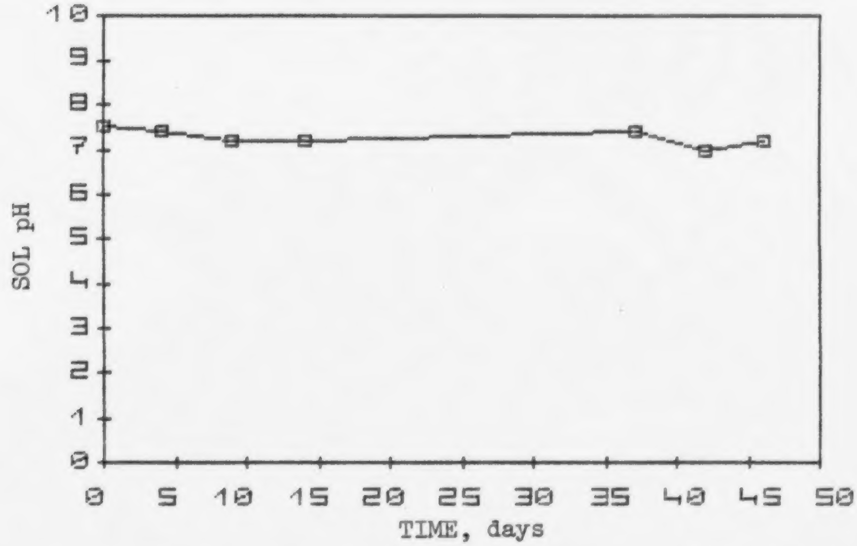

Figure C.196. Soluble pH of effluent synthetic sewage at Point B in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

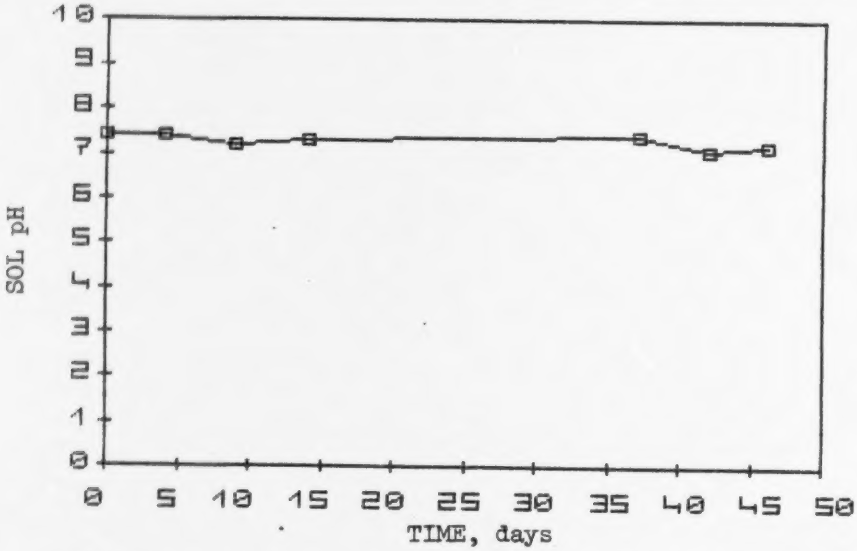

Figure C.197. Soluble pH of effluent synthetic sewage in the second unit of the two unit reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980. Start-up of the second unit was September 5, 1980.

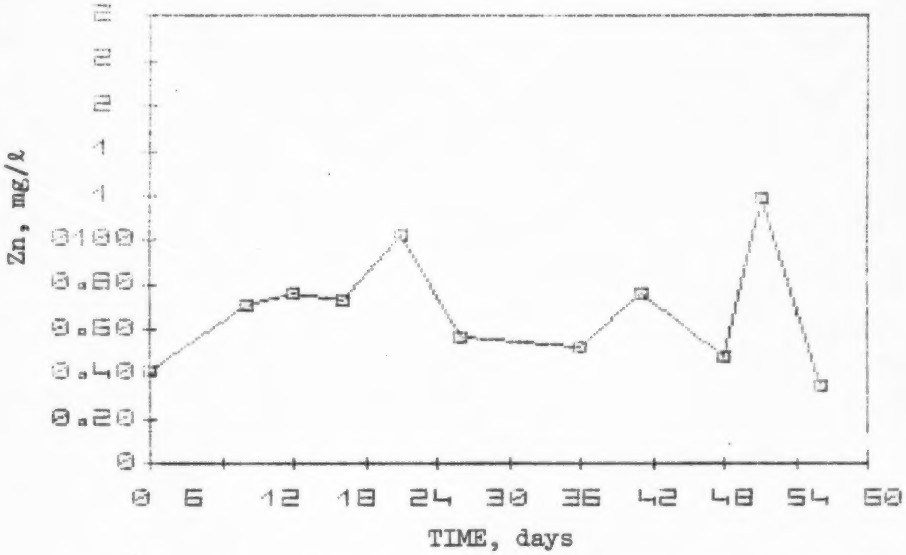

Figure C.198. Zinc concentration of influent synthetic sewage delivered to the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

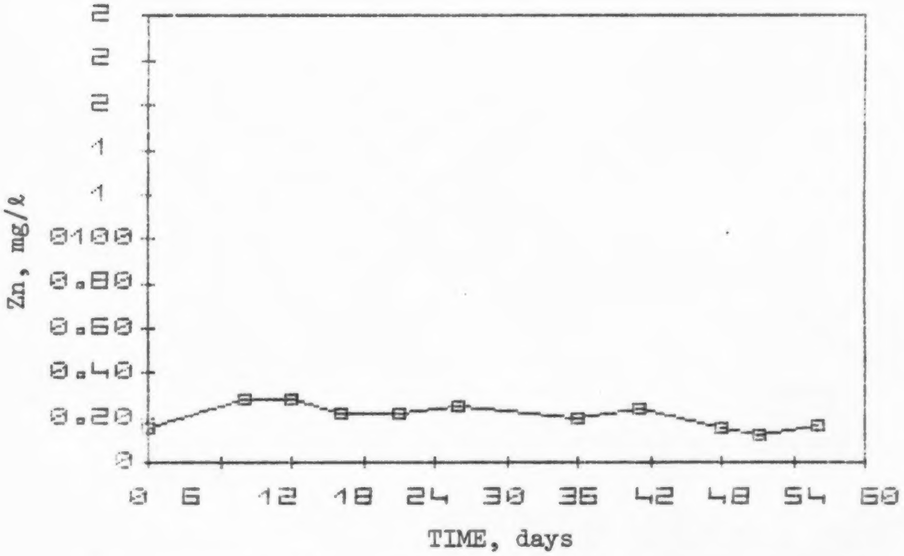

Figure C.199. Zinc concentration of influent synthetic sewage at Point A in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

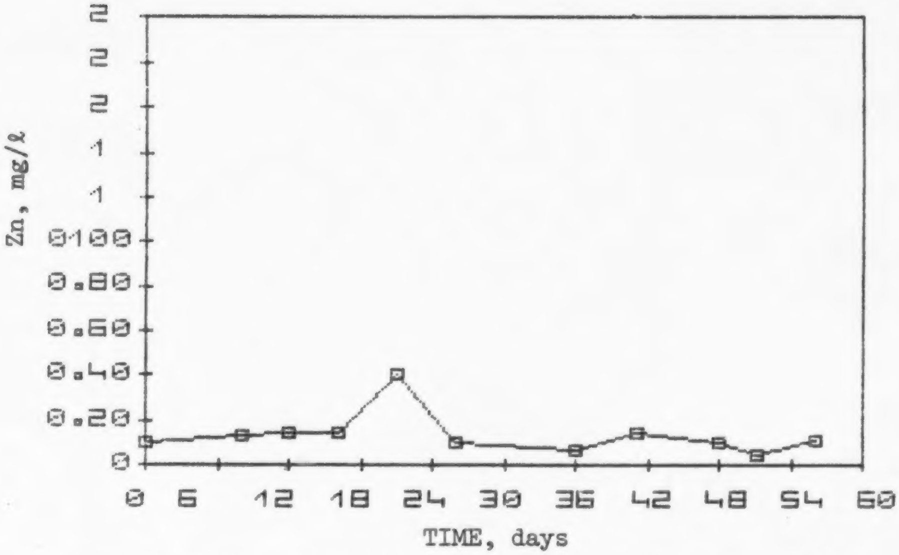

Figure C.200. Zinc concentration of influent synthetic sewage at Point B in the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

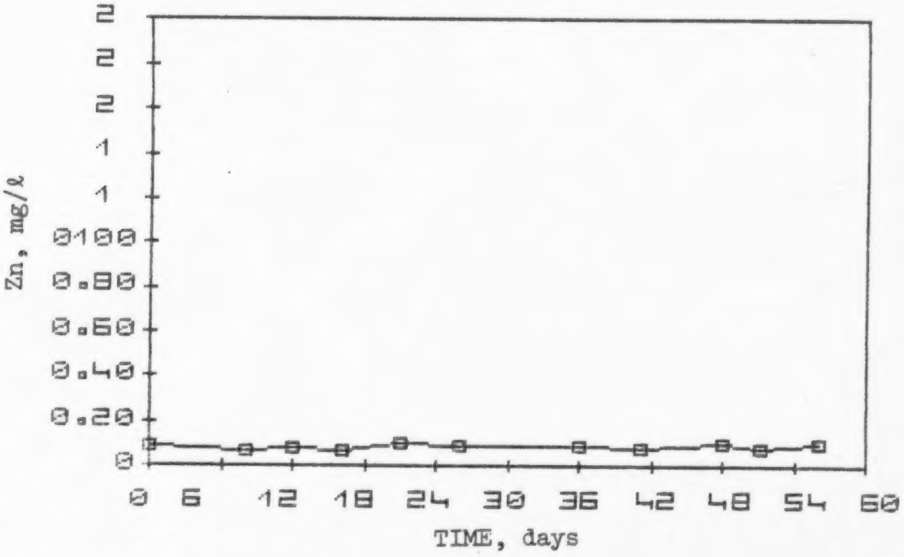

Figure C.201. Zinc concentration of effluent synthetic sewage from the reed canary grass Cornell NFT in Phase 1. First day of analysis was March 19, 1980.

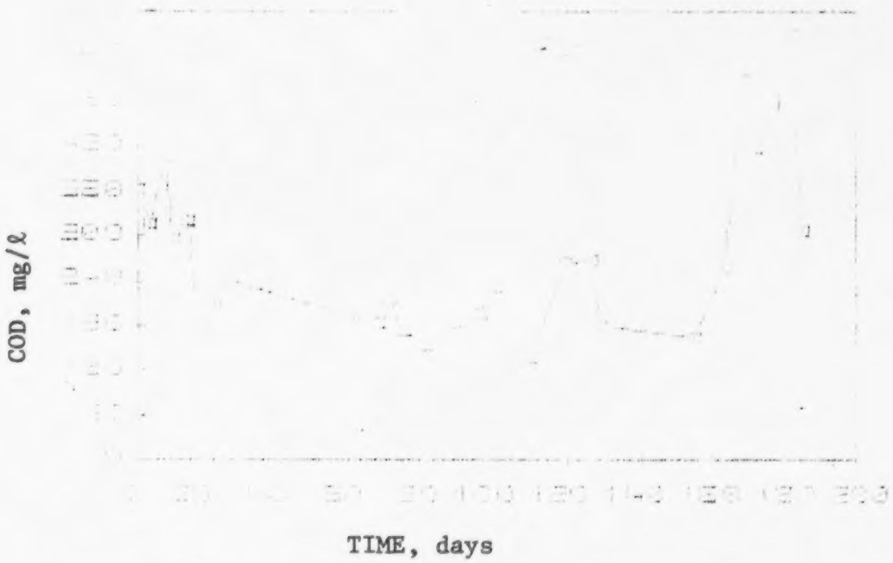

Figure C.202. Chemical oxygen demand concentration of influent synthetic sewage to the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

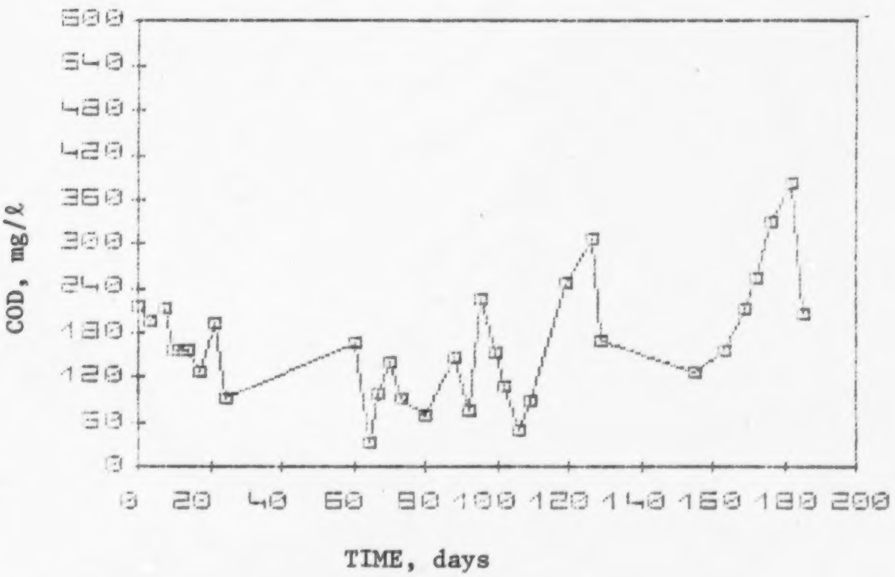

Figure C.203. Chemical oxygen demand concentration of effluent synthetic sewage in Phase 1. First day of analysis was February 16, 1981.

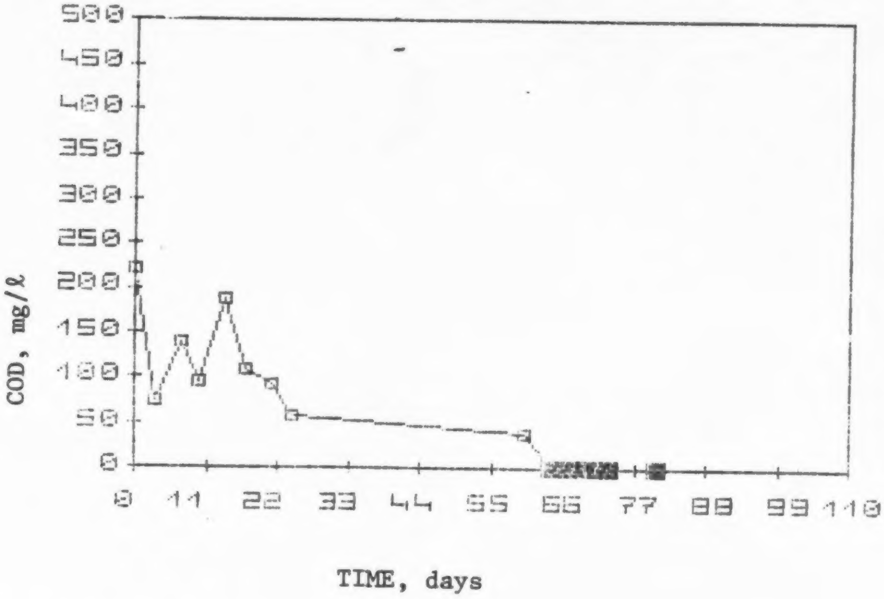

Figure C.204. Chemical oxygen demand concentration of influent synthetic sewage to the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

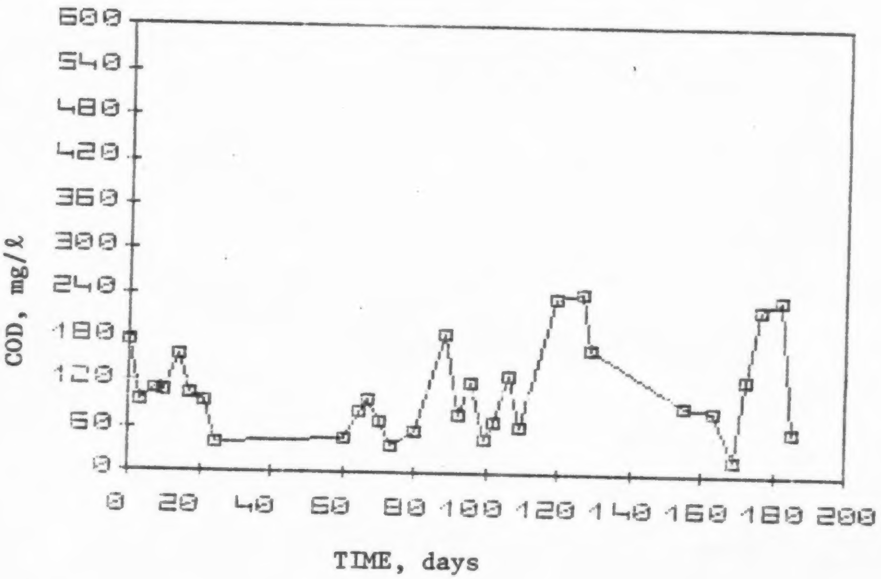

Figure C.205. Chemical oxygen demand concentration of effluent synthetic sewage from the second unit of the three unit Cornell NFT in Phase 1. First day of analysis was February 16, 1981.

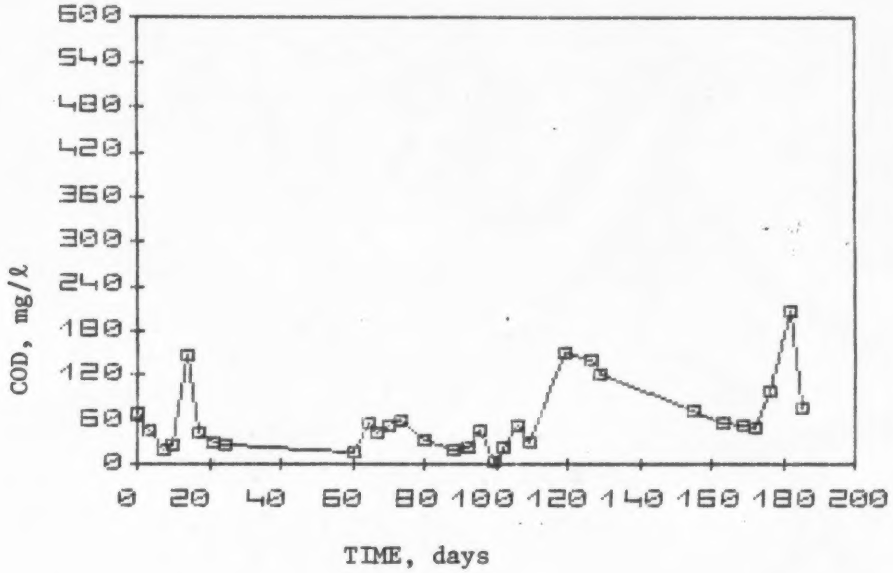

Figure C.206. Chemical oxygen demand concentration of effluent synthetic sewage from the third unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

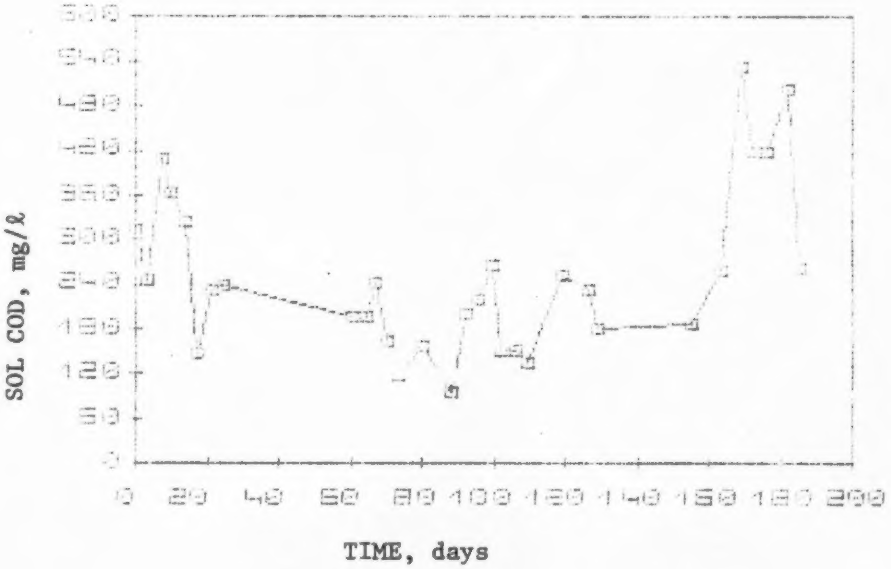

Figure C.207. Soluble chemical oxygen demand concentration of influent synthetic sewage to the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

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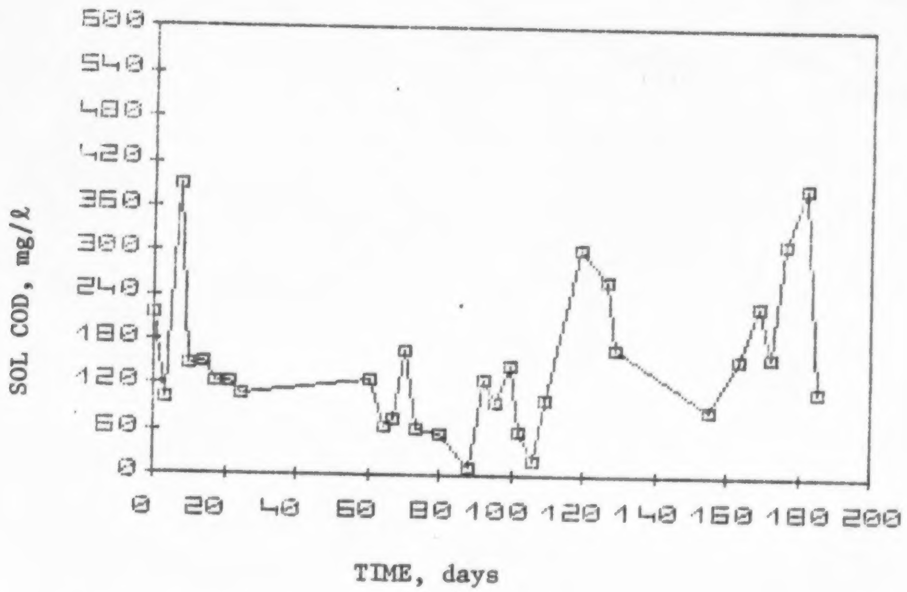

Figure C.208. Soluble chemical oxygen demand concentration of effluent synthetic sewage from the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

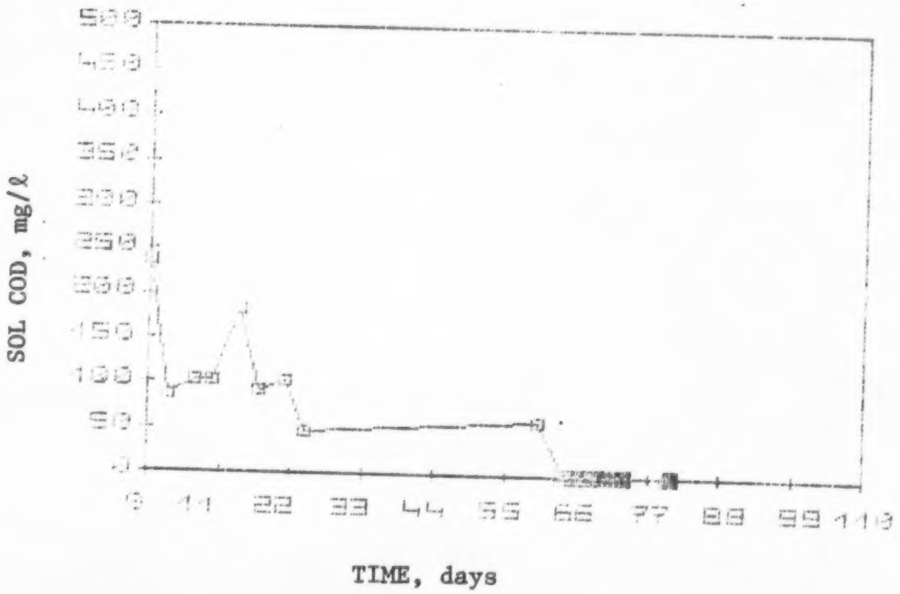

Figure C.209. Soluble chemical oxygen demand concentration of influent synthetic sewage to the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

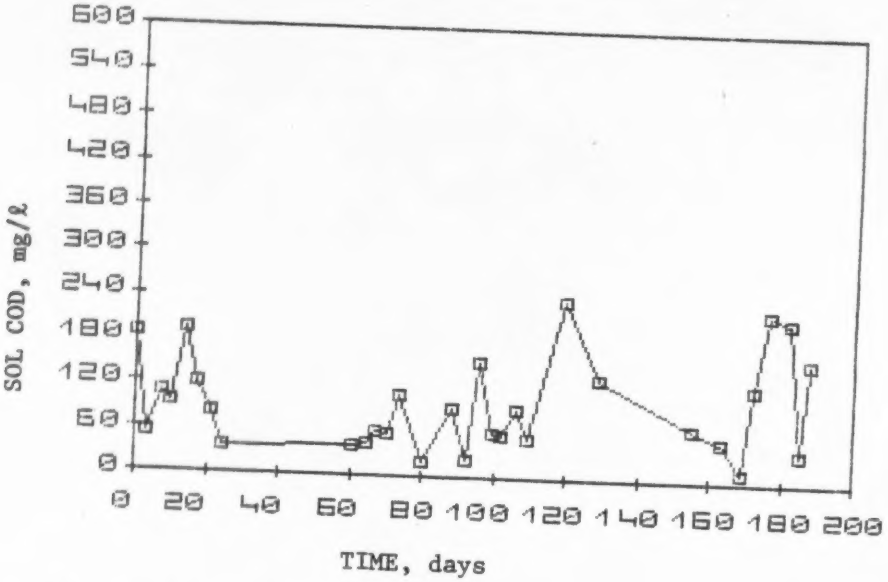

Figure C.210. Soluble chemical oxygen demand concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

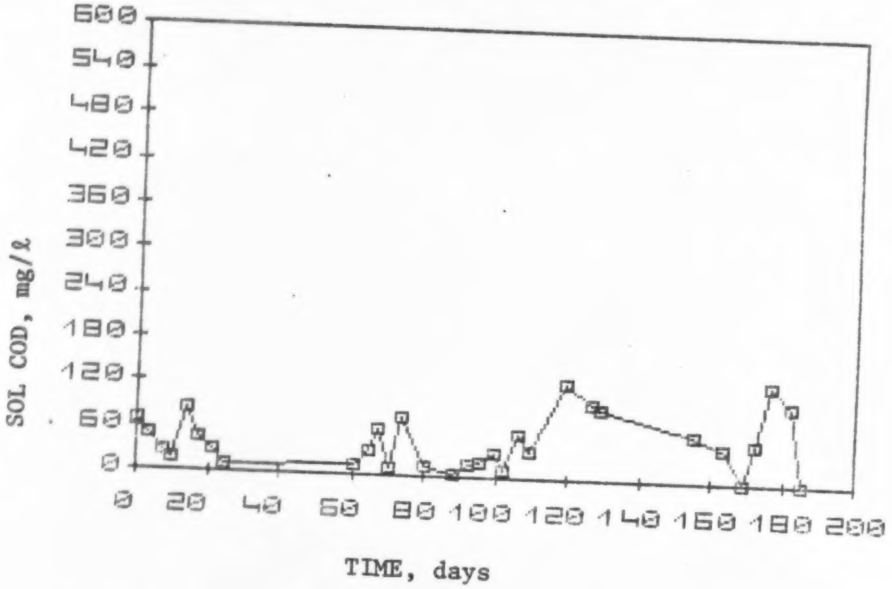

Figure C.211. Soluble chemical oxygen demand concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

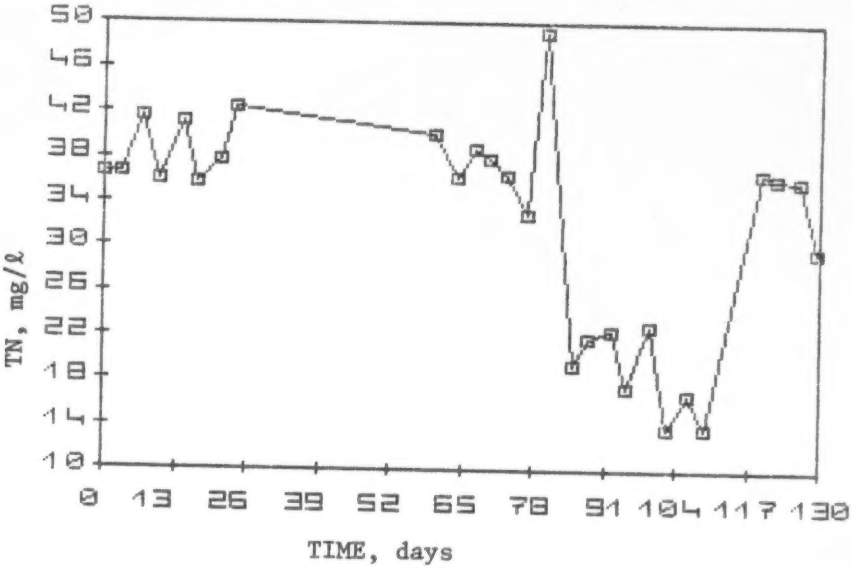

Figure C.212. Total nitrogen concentration of influent synthetic sewage to the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

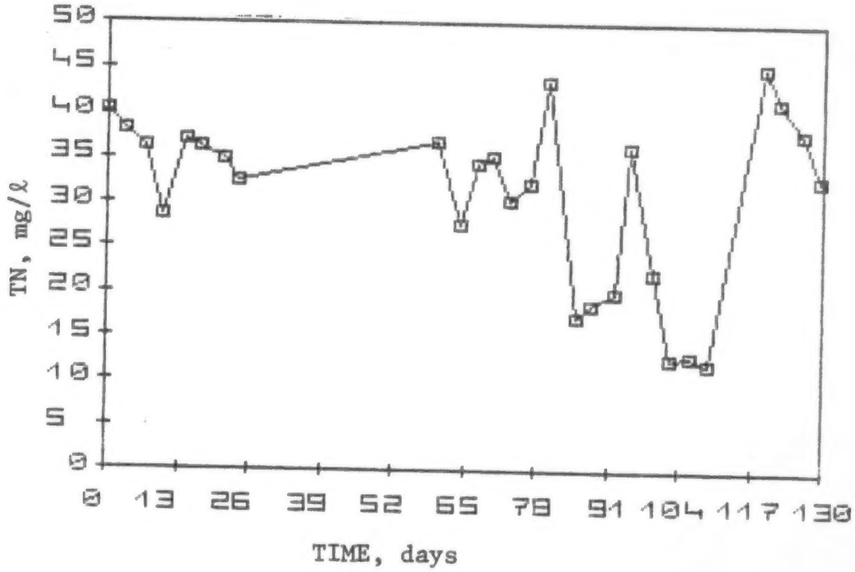

Figure C.213. Total nitrogen concentration of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

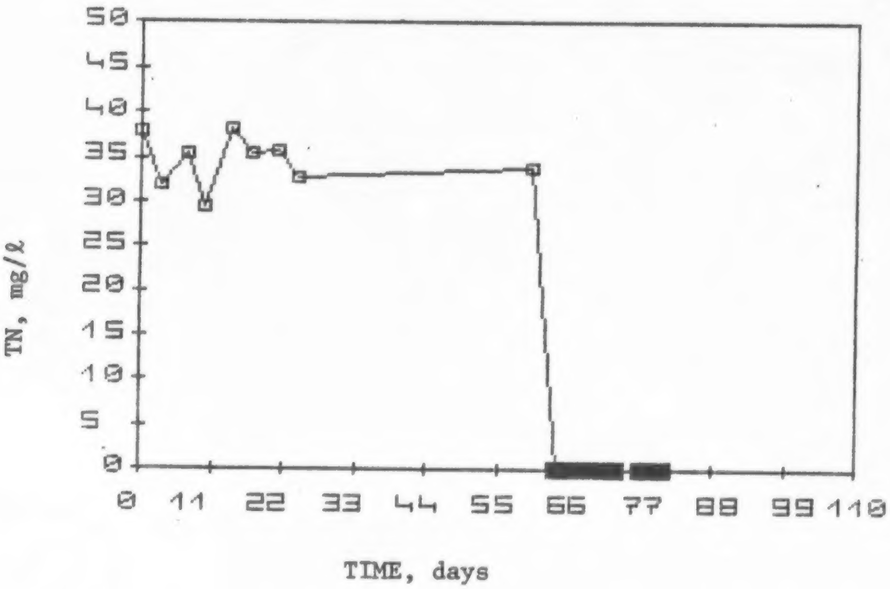

Figure C.214. Total nitrogen concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

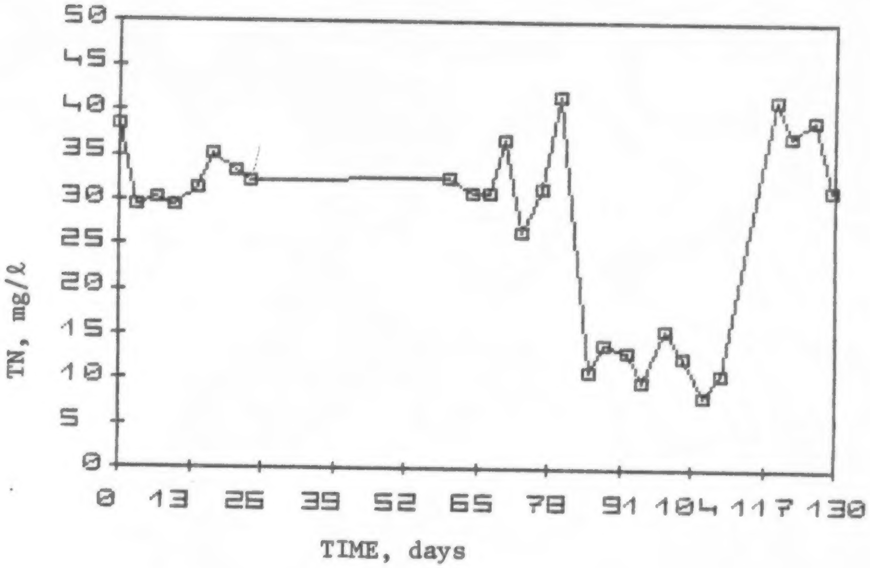

Figure C.215. Total nitrogen concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

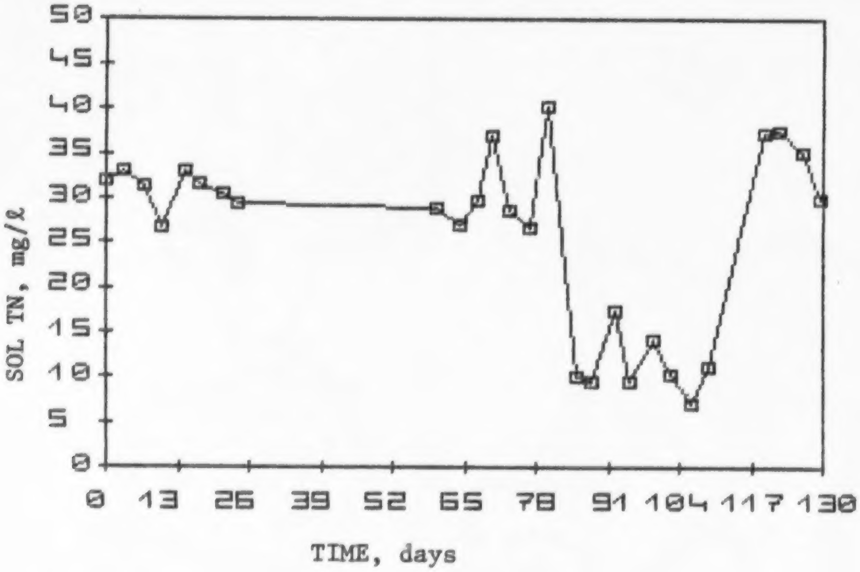

Figure C.216. Total nitrogen concentration of effluent synthetic sewage from the third unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

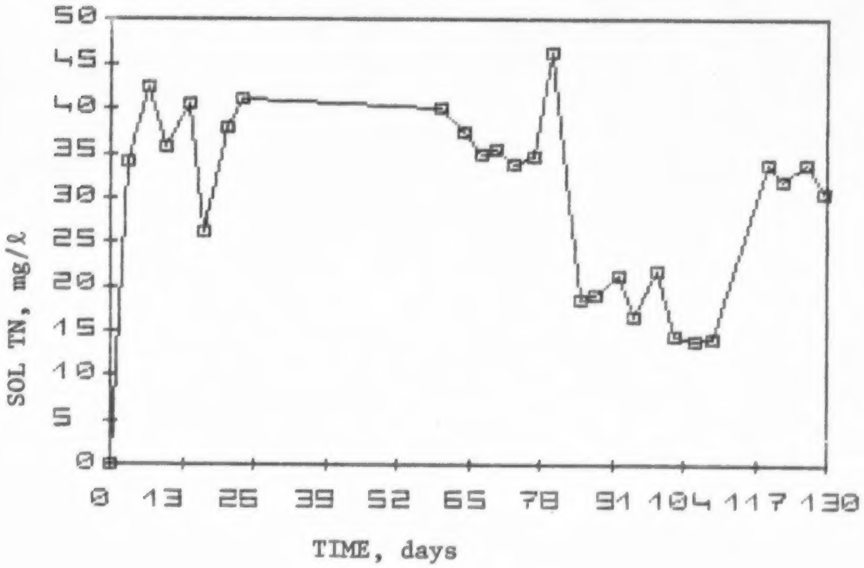

Figure C.217. Soluble total nitrogen concentration of influent synthetic sewage to the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

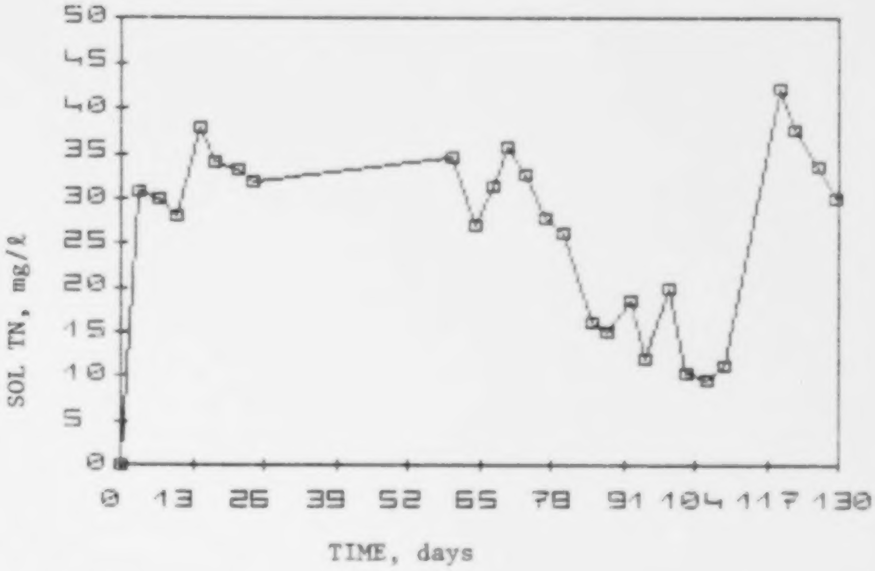

Figure C.218. Soluble total nitrogen concentration of effluent synthetic sewage from the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

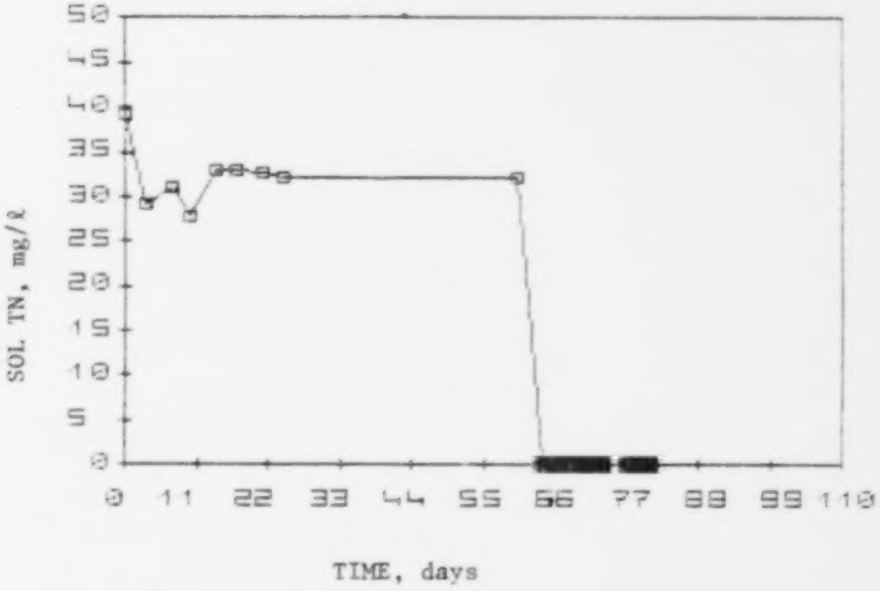

Figure C.219. Soluble total nitrogen concentration of influent synthetic sewage to the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

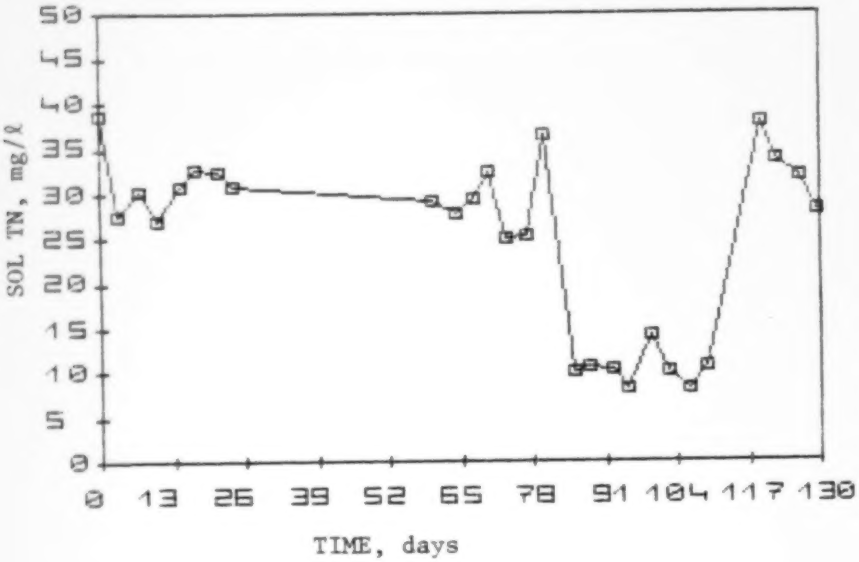

Figure C.220. Soluble total nitrogen concentration of effluent synthetic sewage from the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

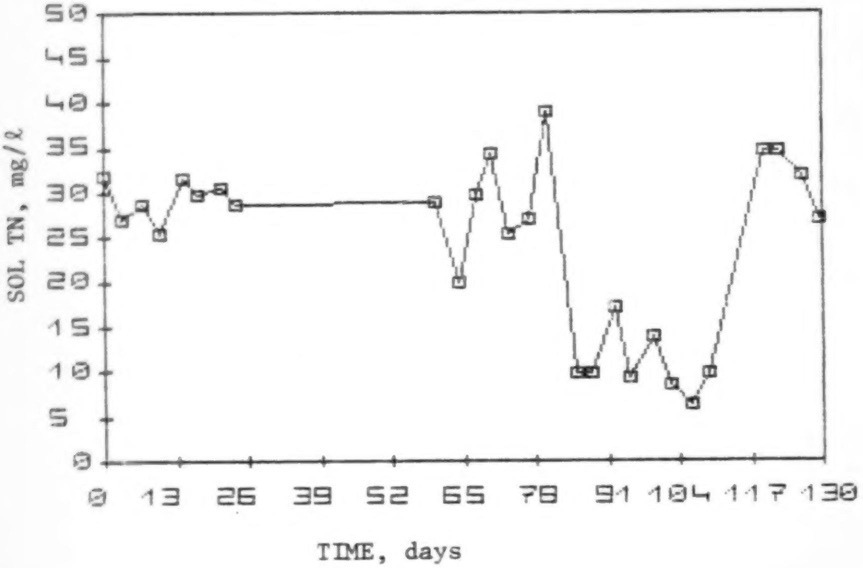

Figure C.221. Soluble nitrogen concentration of effluent synthetic sewage from the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

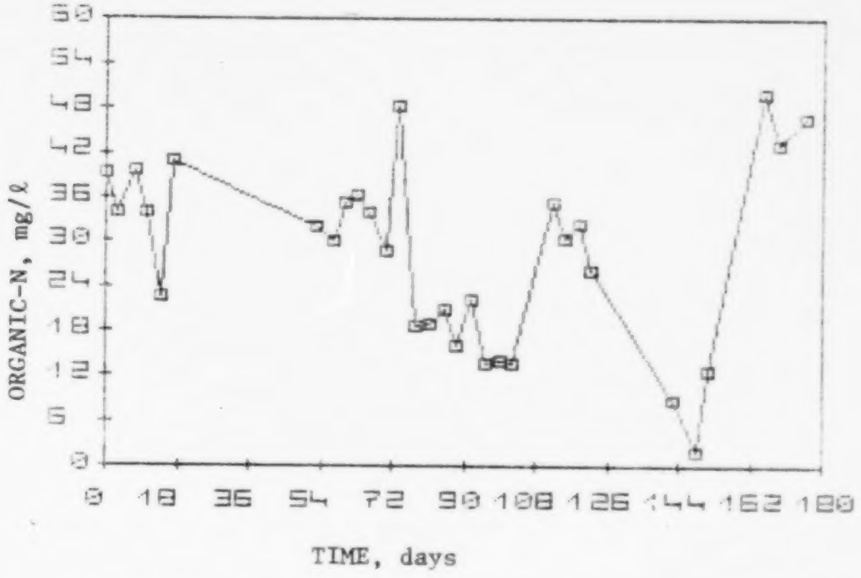

Figure C.222. Organic nitrogen concentration of influent synthetic sewage to the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

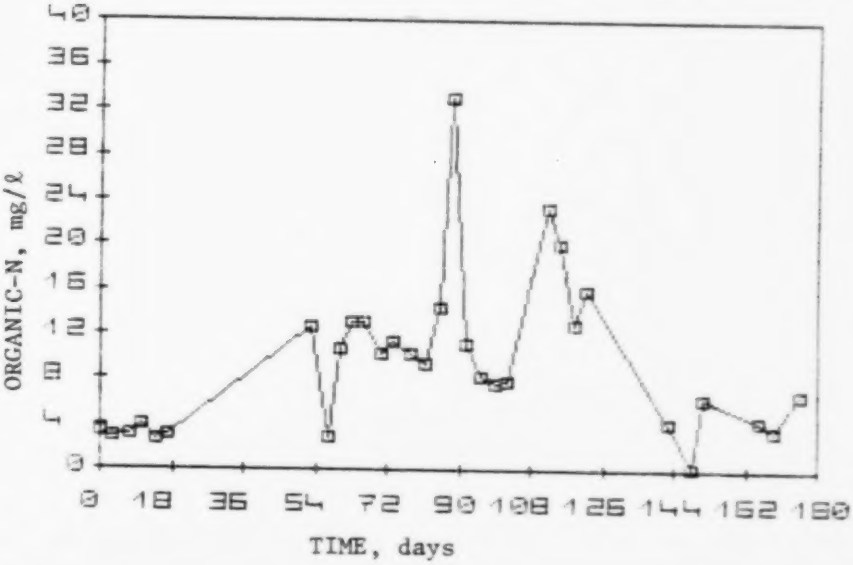

Figure C.223. Organic nitrogen concentration of effluent synthetic sewage from the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

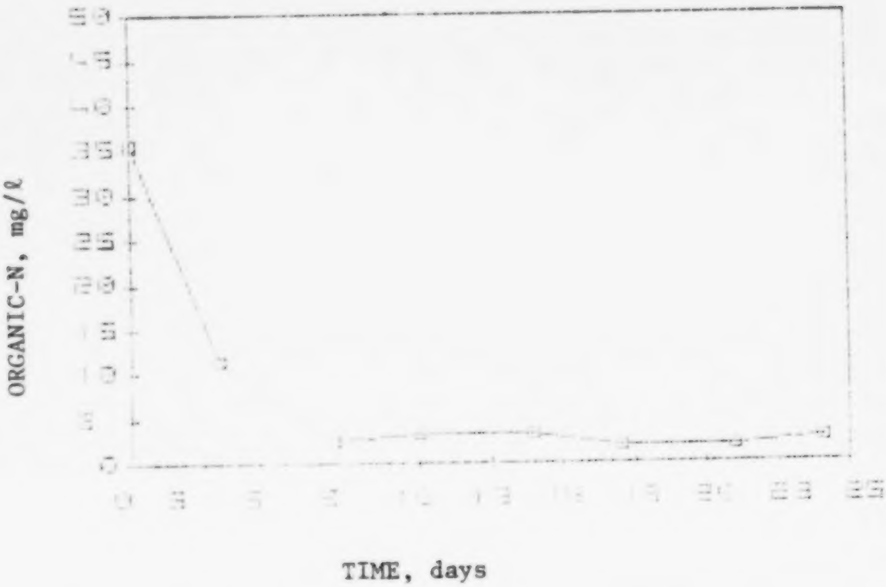

Figure C.224. Organic nitrogen concentration of influent synthetic sewage to the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

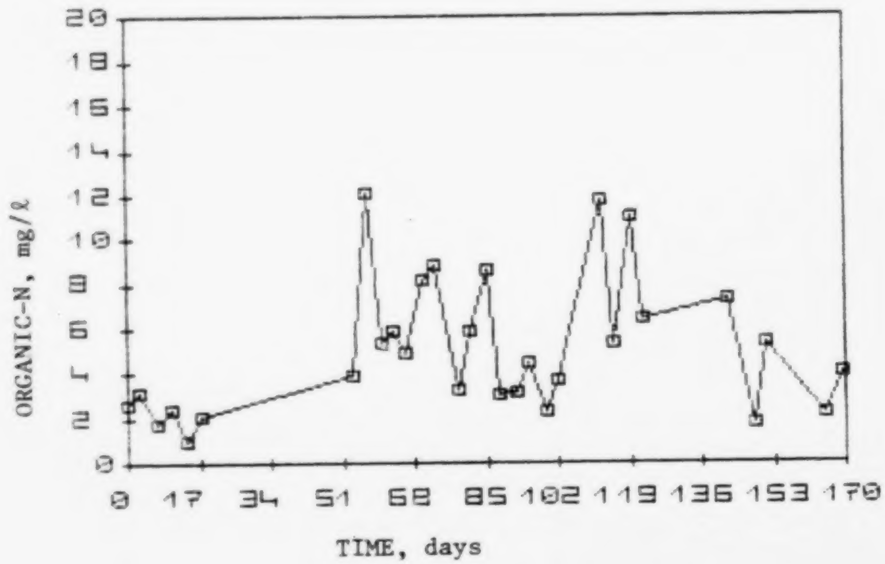

Figure C.225. Organic nitrogen concentration of effluent synthetic sewage from the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981

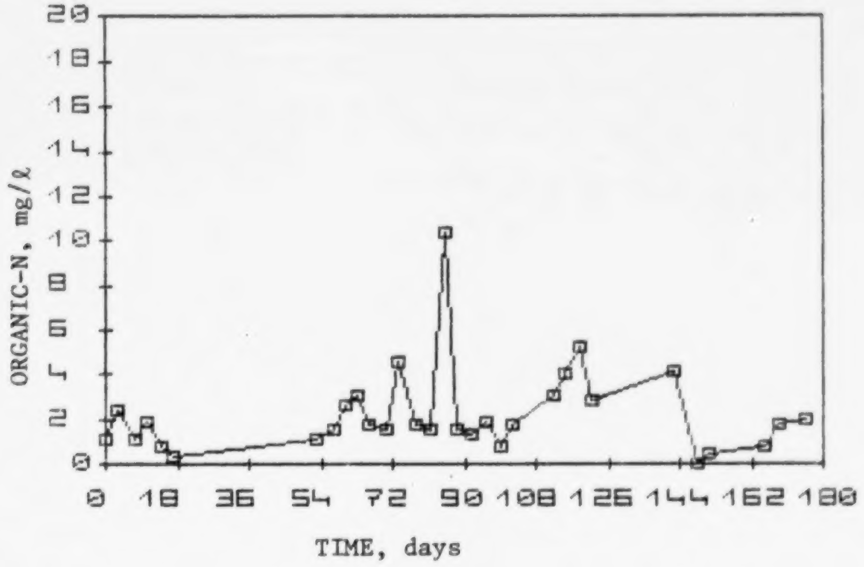

Figure C.226. Organic nitrogen concentration of effluent synthetic sewage from the third unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

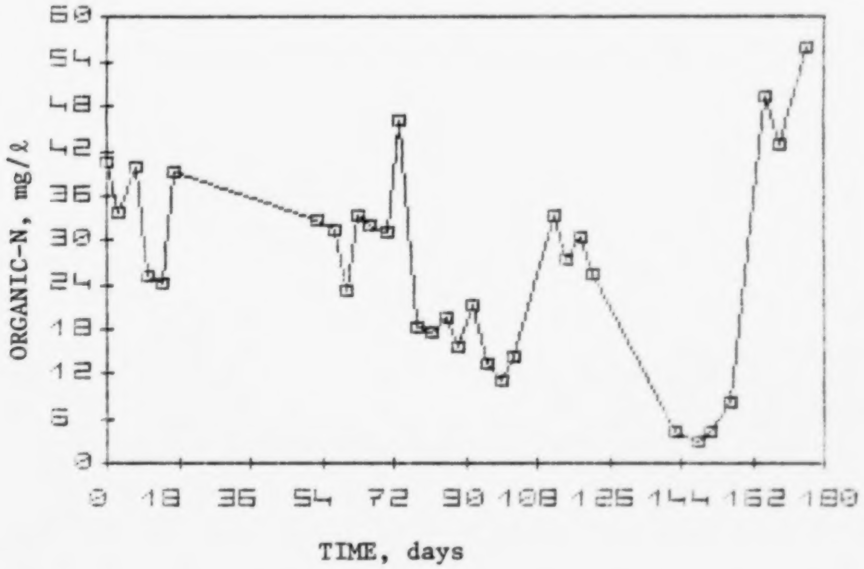

Figure C.227. Soluble organic nitrogen concentration of influent synthetic sewage to the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

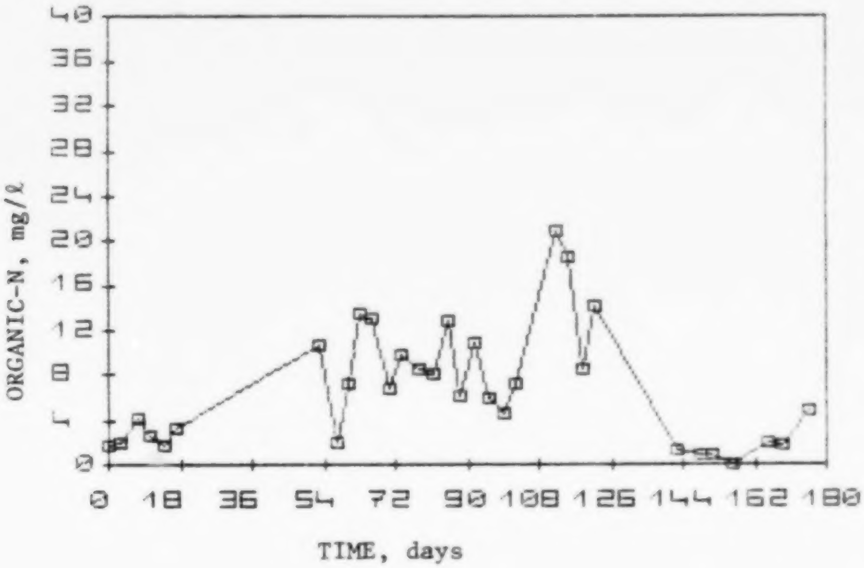

Figure C.228. Soluble organic nitrogen concentration of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

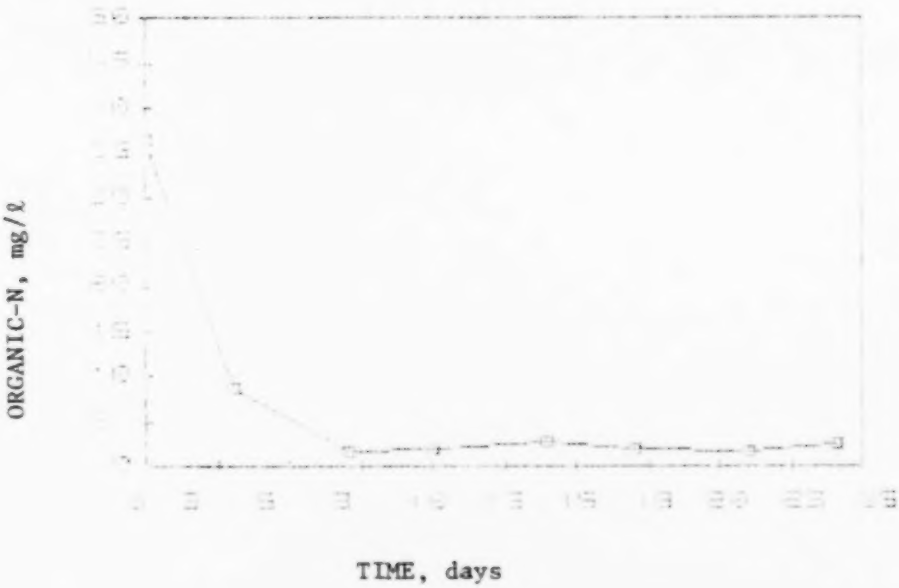

Figure C.229. Soluble organic nitrogen concentration of influent synthetic sewage to the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

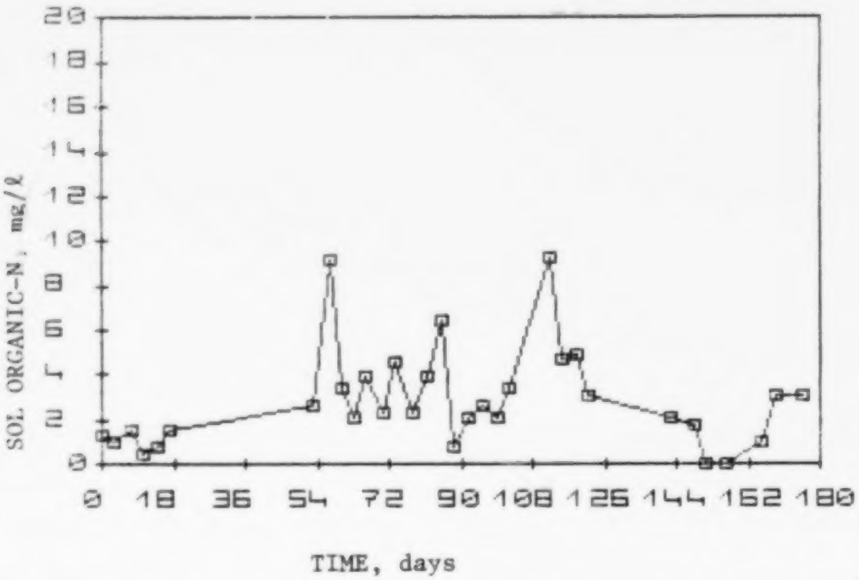

Figure C.230. Soluble organic nitrogen concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

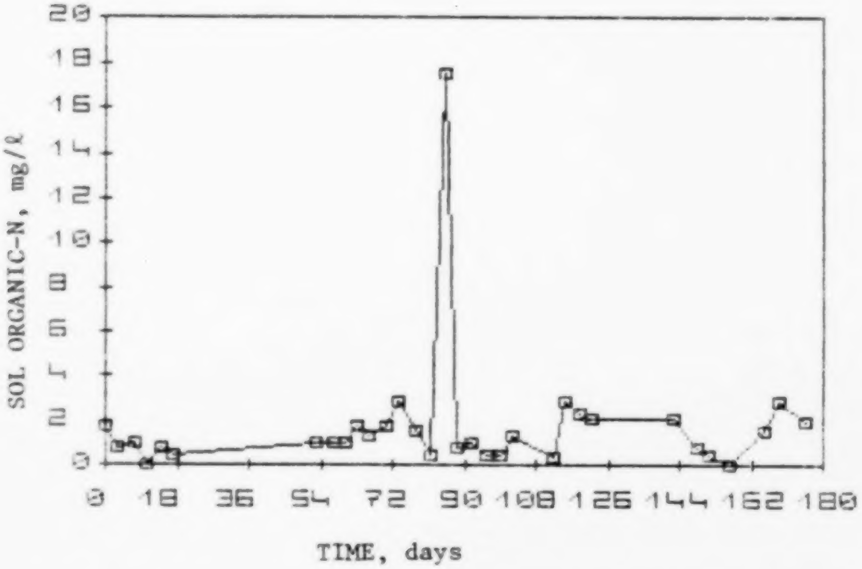

Figure C.231. Soluble organic nitrogen concentration of effluent synthetic sewage from the third unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

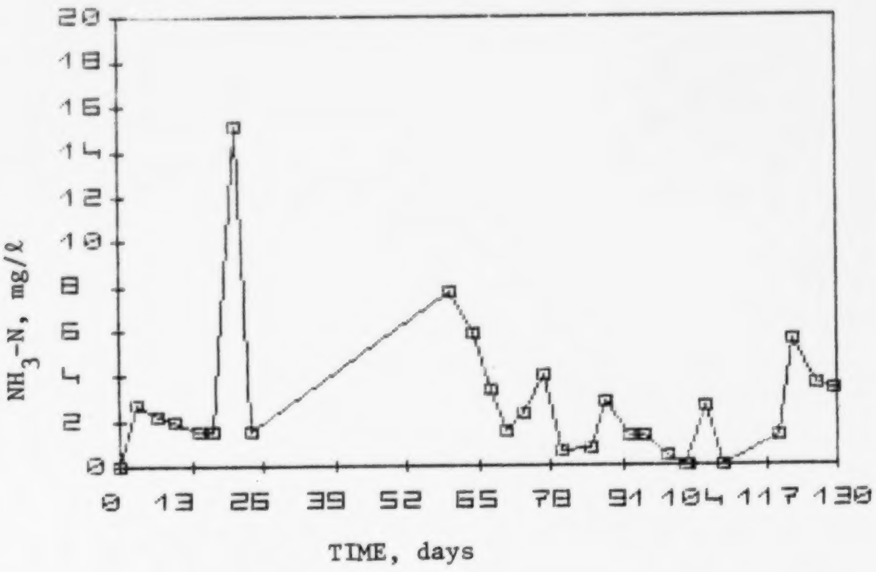

Figure C.232. Ammonia nitrogen concentration of influent synthetic sewage to the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

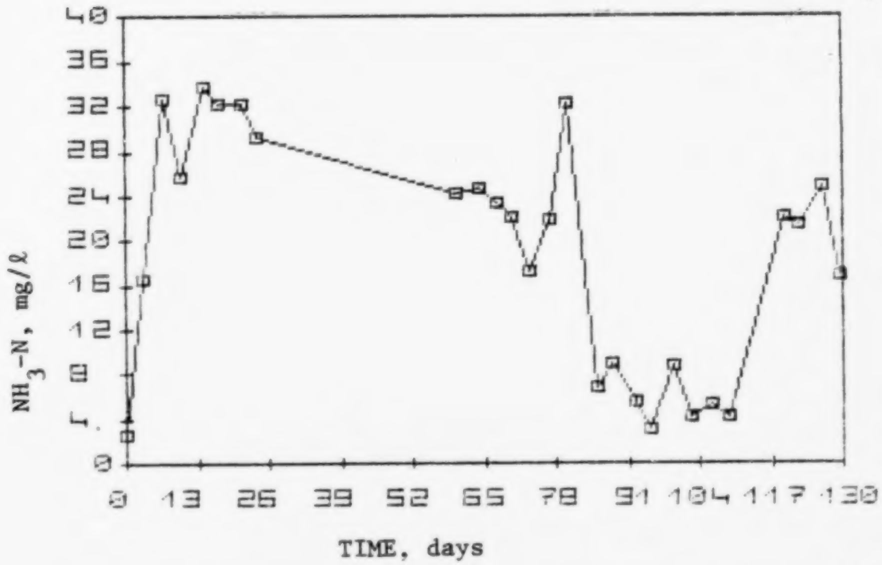

Figure C.233. Ammonia nitrogen concentration of effluent synthetic sewage from the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

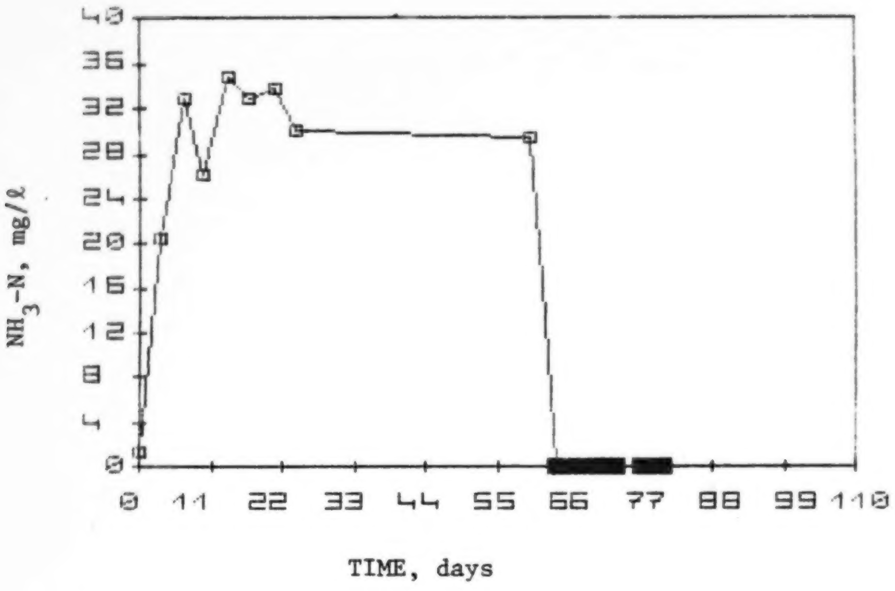

Figure C.234. Ammonia nitrogen concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

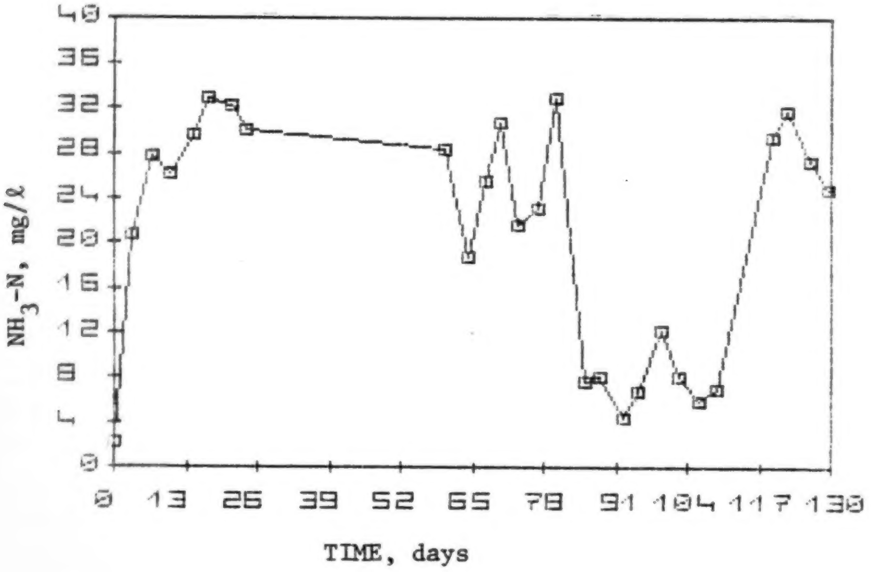

Figure C.235. Ammonia nitrogen concentration of effluent synthetic sewage from the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

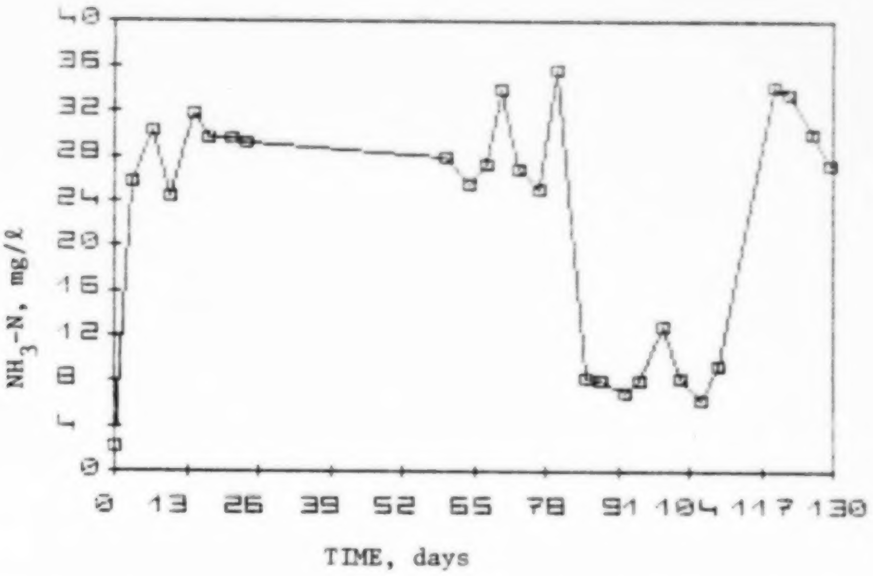

Figure C.236. Ammonia nitrogen concentration of effluent synthetic sewage from the third unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

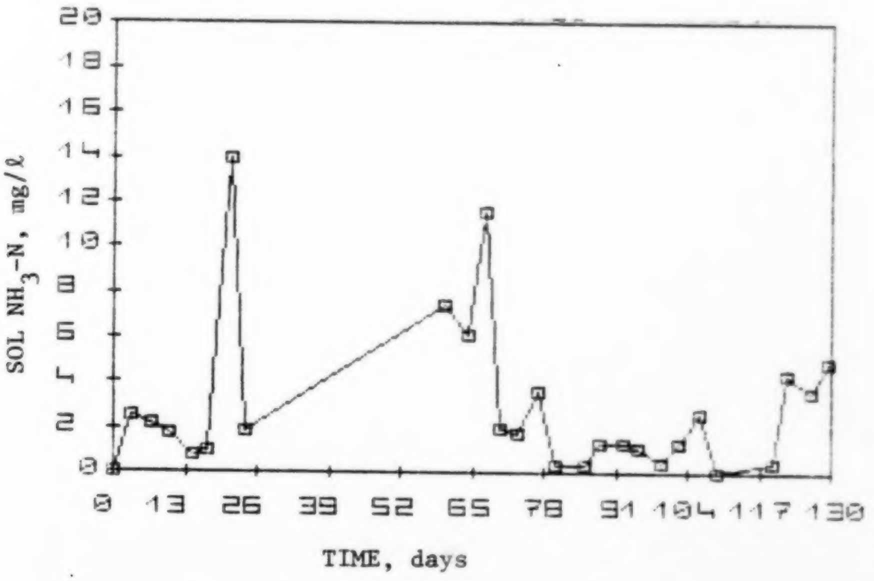

Figure C.237. Soluble ammonia nitrogen concentration of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

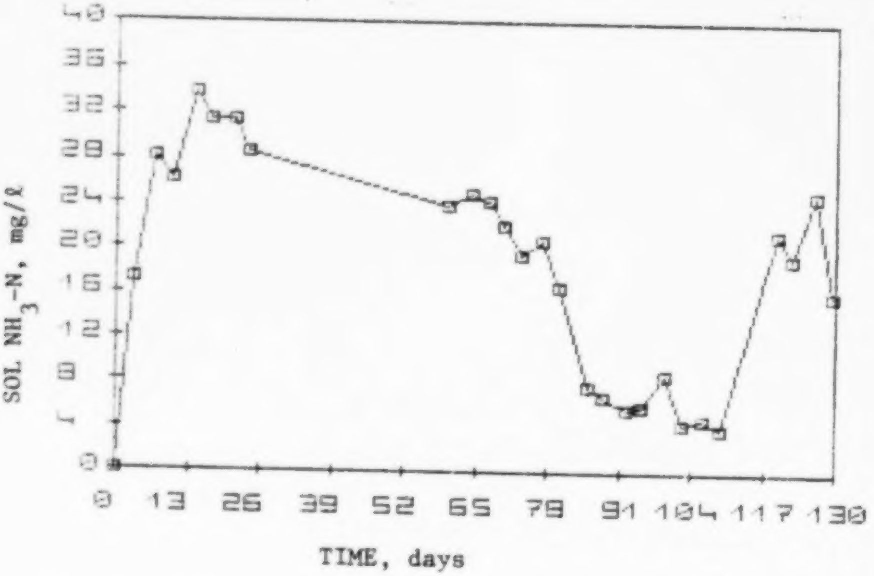

Figure C.238. Soluble ammonia nitrogen concentration of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

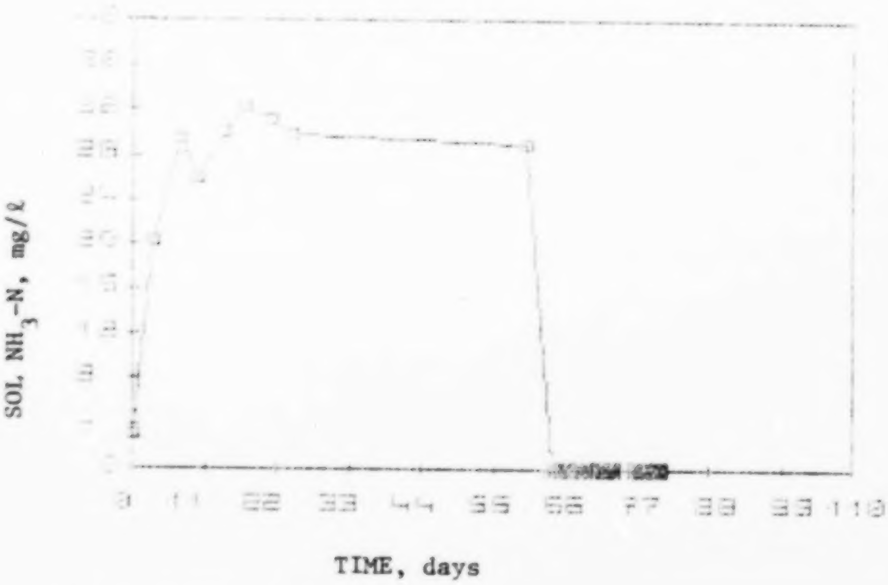

Figure C.239. Soluble ammonia nitrogen concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

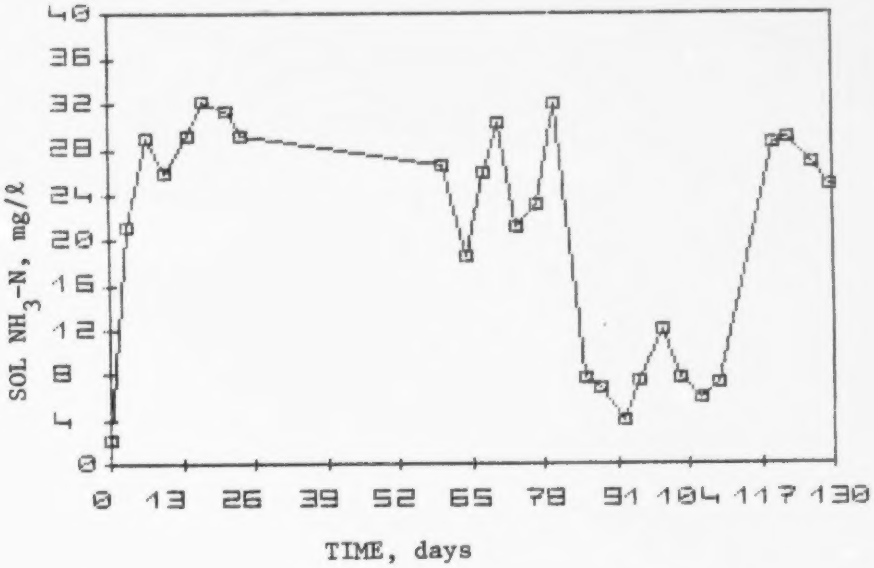

Figure C.240. Soluble ammonia nitrogen concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

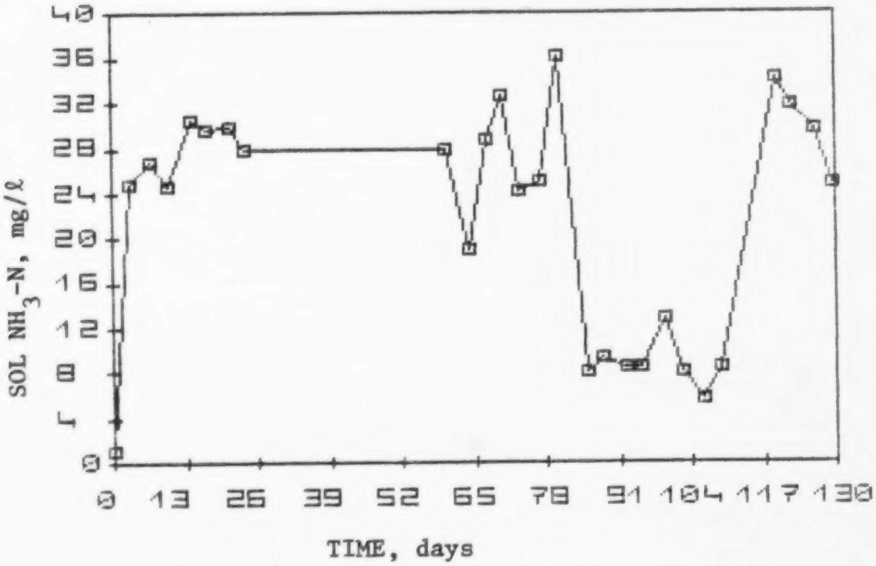

Figure C.241. Soluble ammonia nitrogen concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

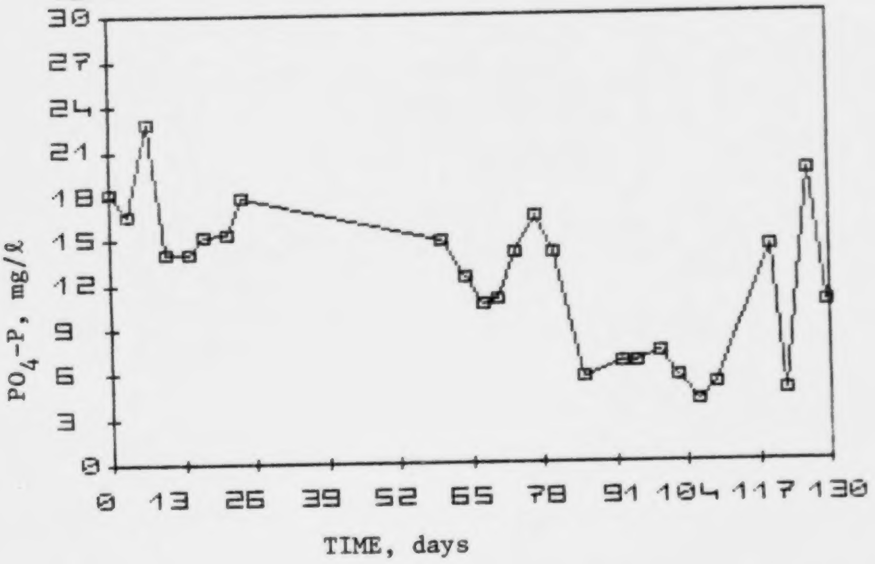

Figure C.242. Orthophosphate concentration of influent synthetic sewage to the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

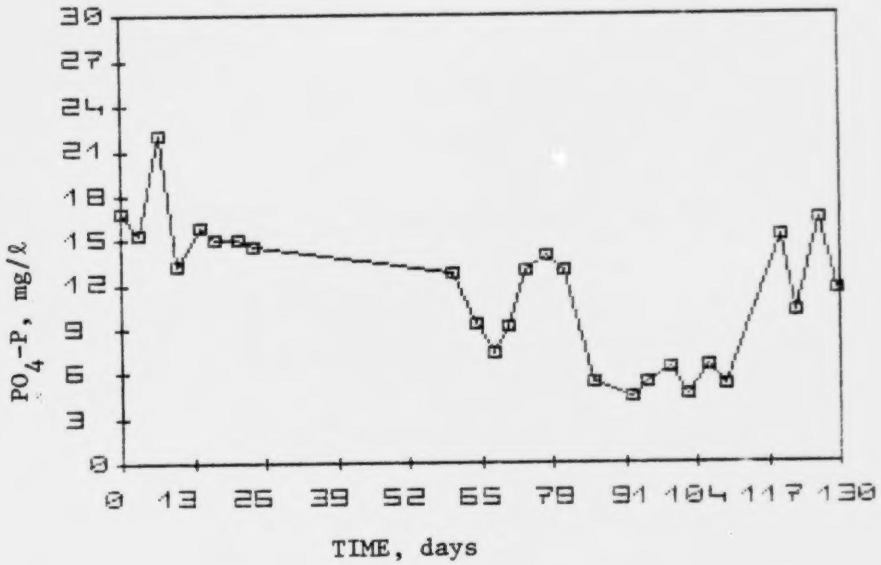

Figure C.243. Orthophosphate concentration of effluent synthetic sewage from the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

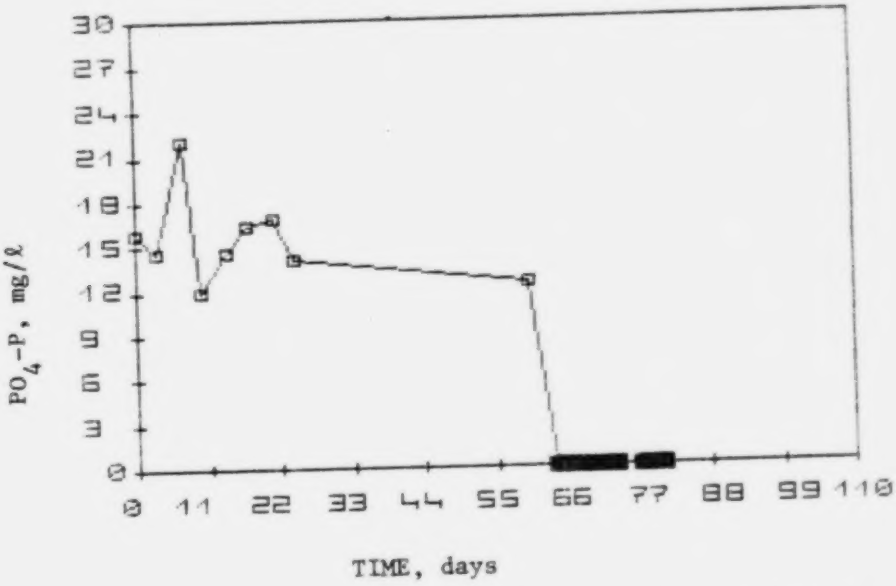

Figure C.244. Orthophosphate concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

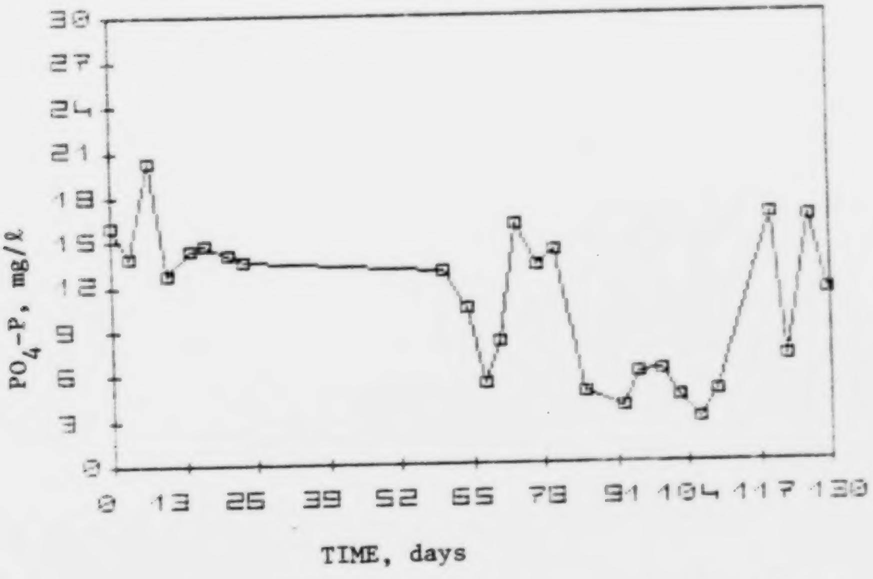

Figure C.245. Orthophosphate concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

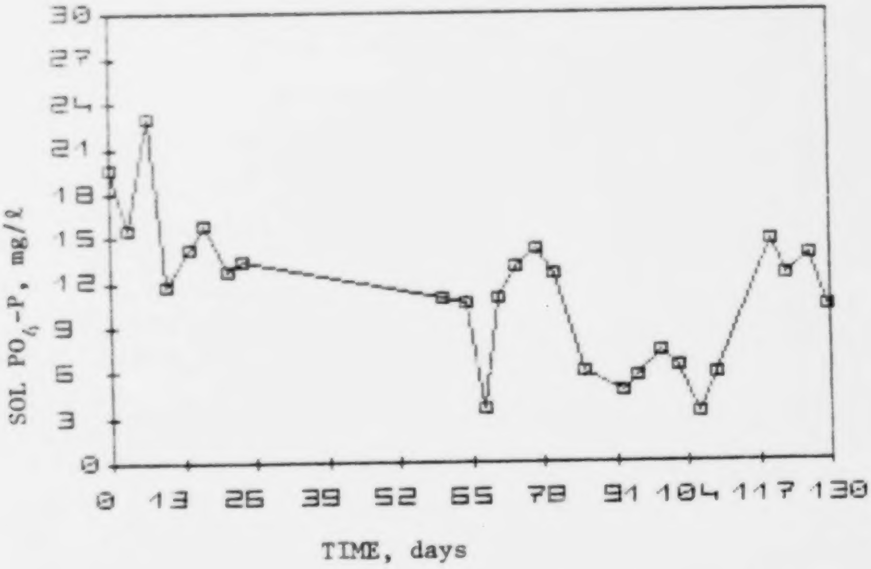

Figure C.246. Orthophosphate concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

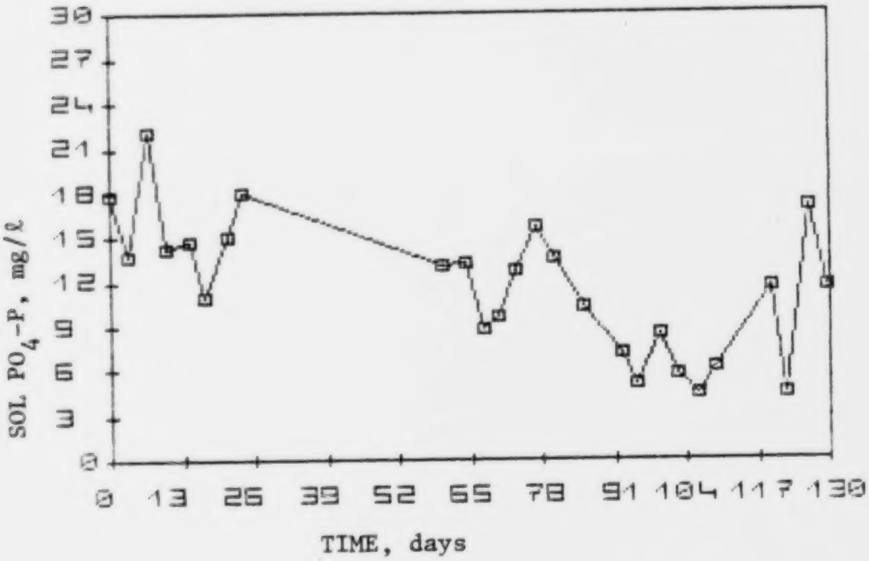

Figure C.247. Soluble orthophosphate concentration of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

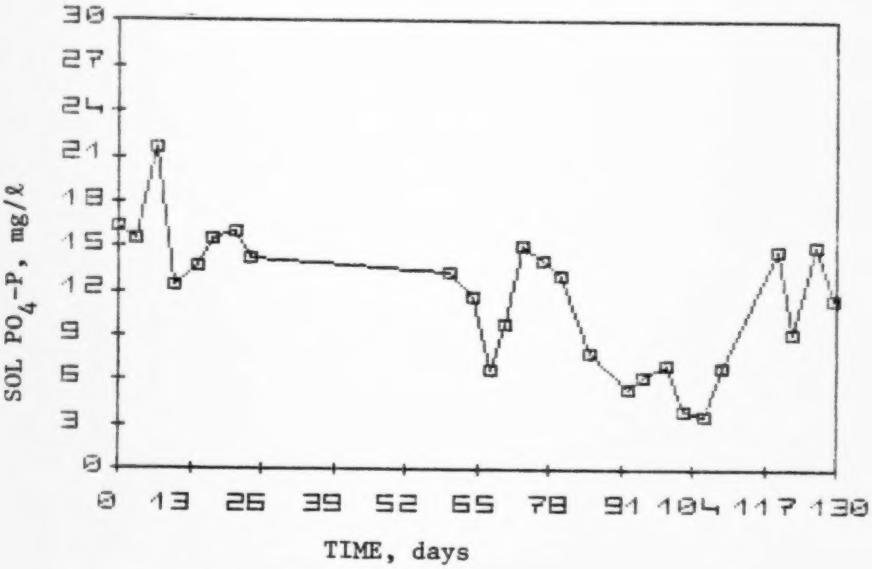

Figure C.248. Soluble orthophosphate concentration of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

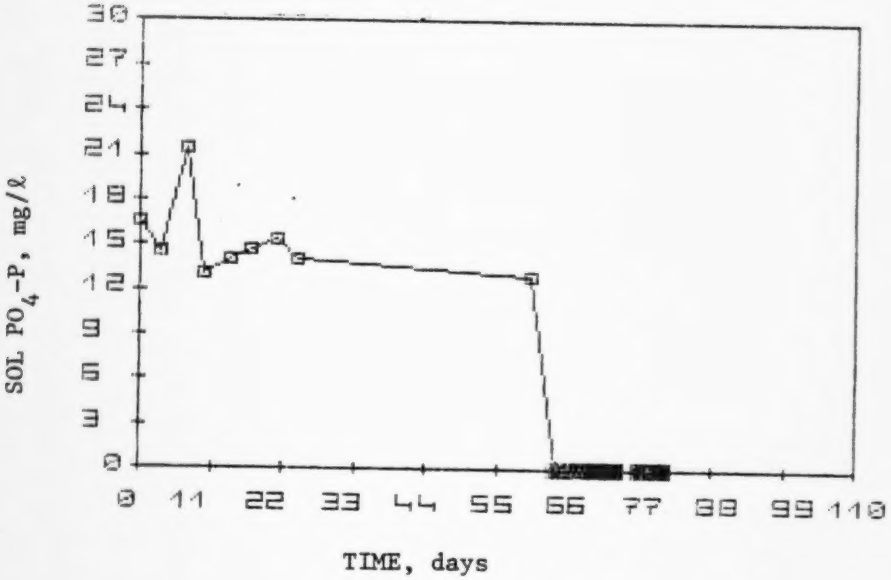

Figure C.249. Soluble orthophosphate concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

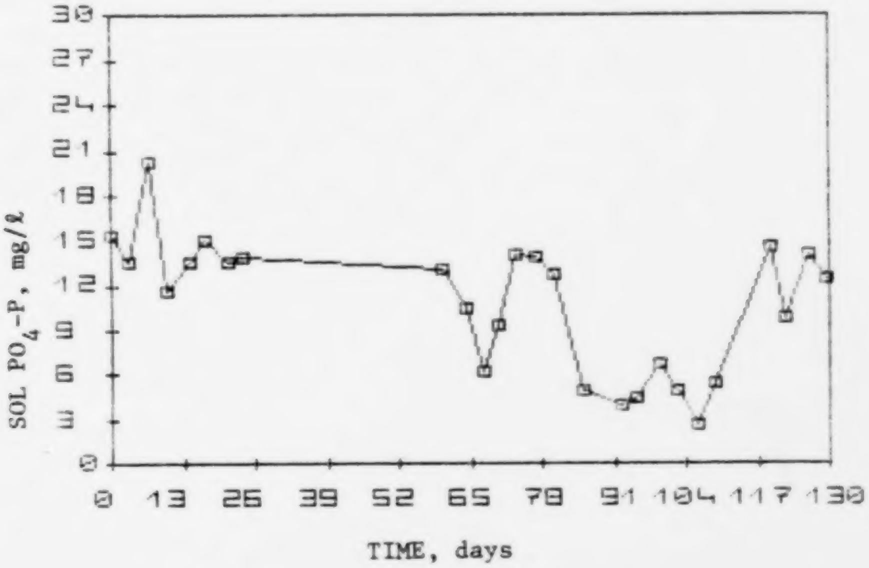

Figure C.250. Soluble orthophosphate concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

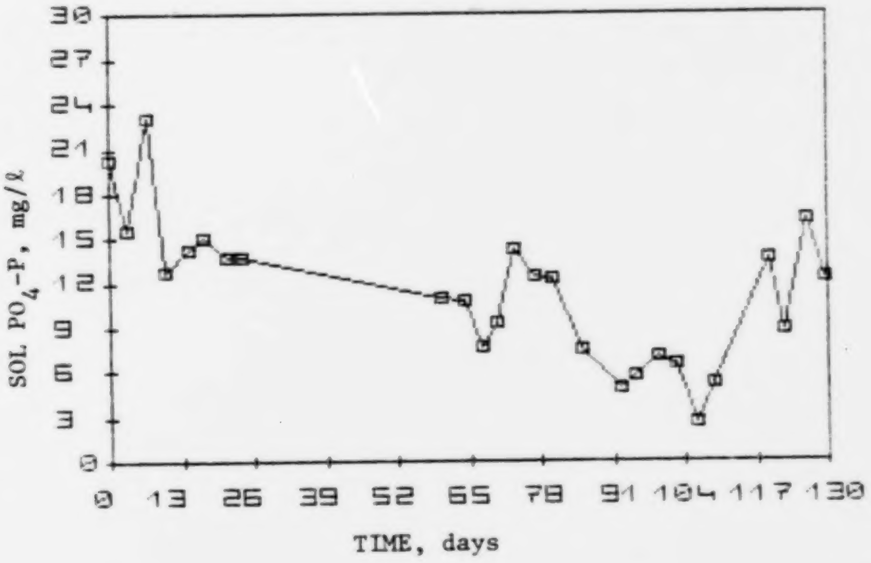

Figure C.251. Soluble orthophosphate concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

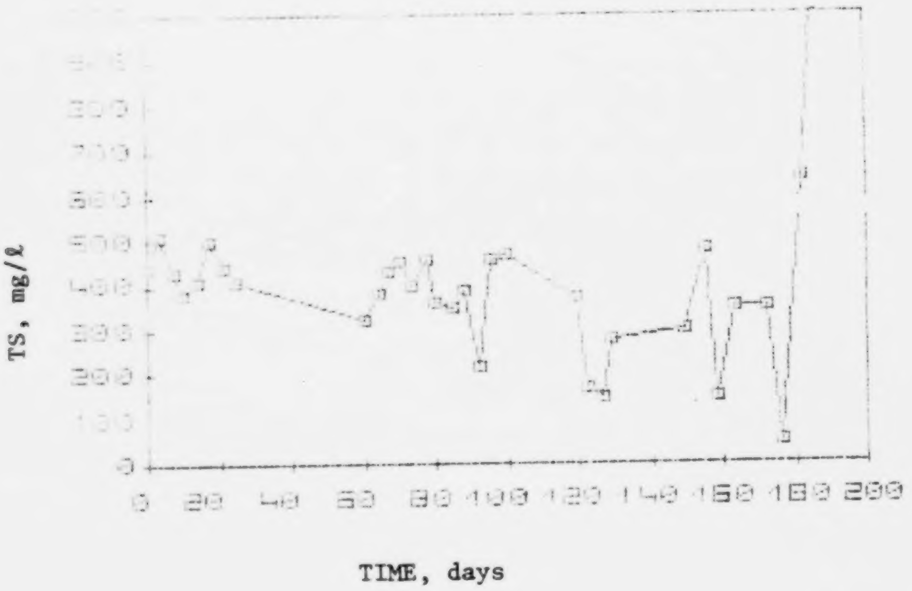

Figure C.252. Total solids concentration of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

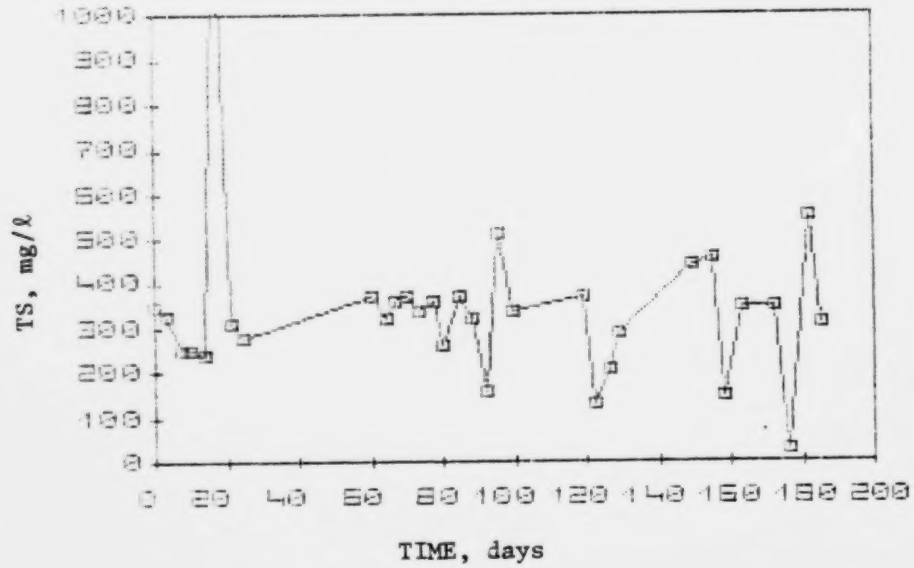

Figure C.253. Total solids concentration of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

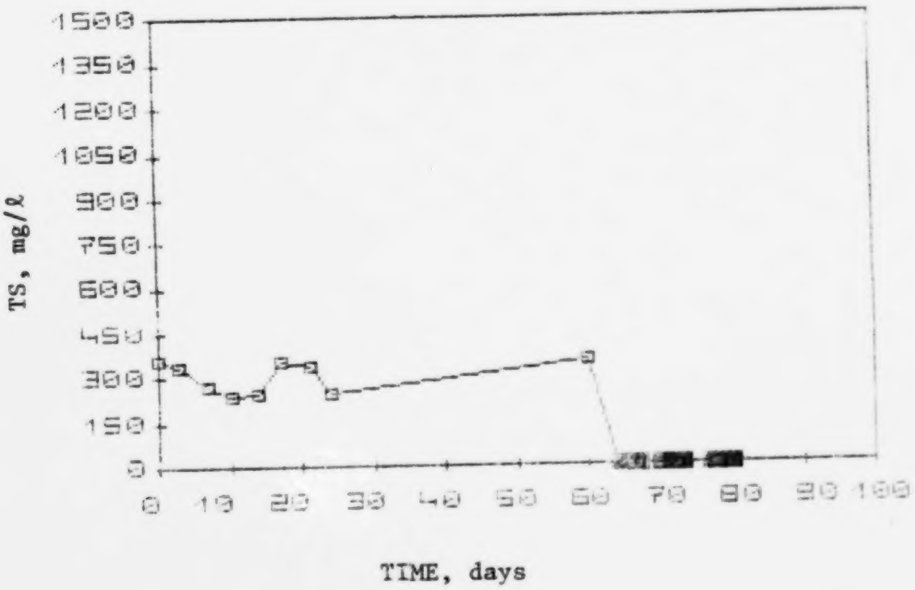

Figure C.254. Total solids concentration of influent synthetic sewage to the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

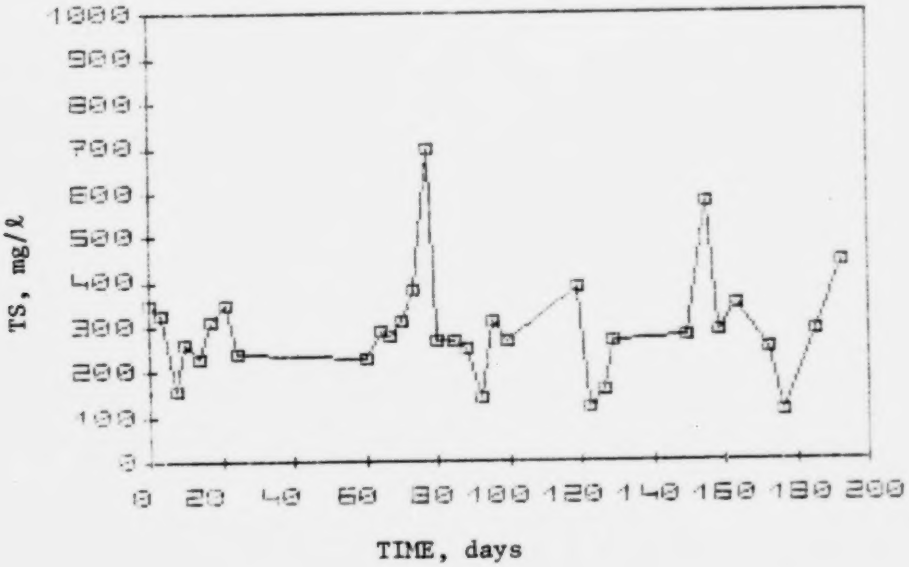

Figure C.255. Total solids concentration of effluent synthetic sewage from the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

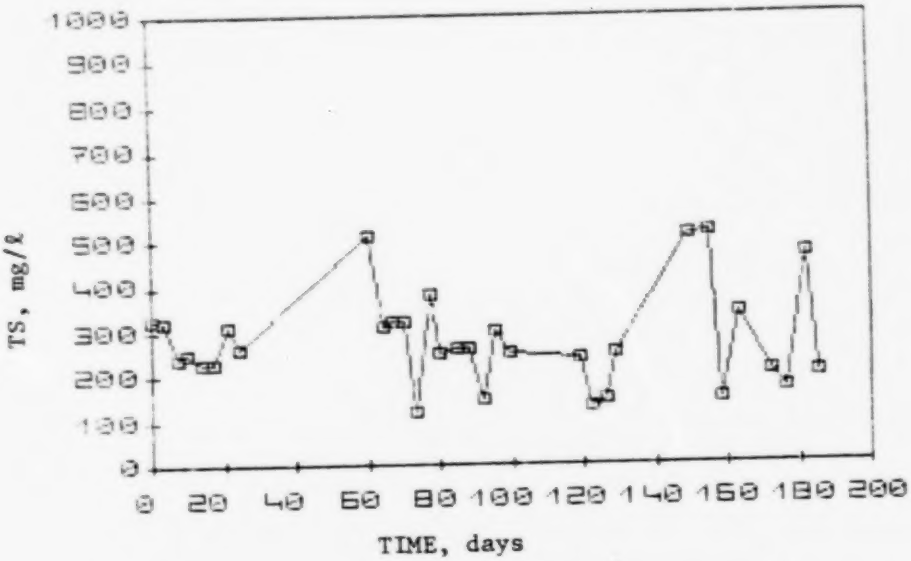

Figure C.256. Total solids concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 1, 1981.

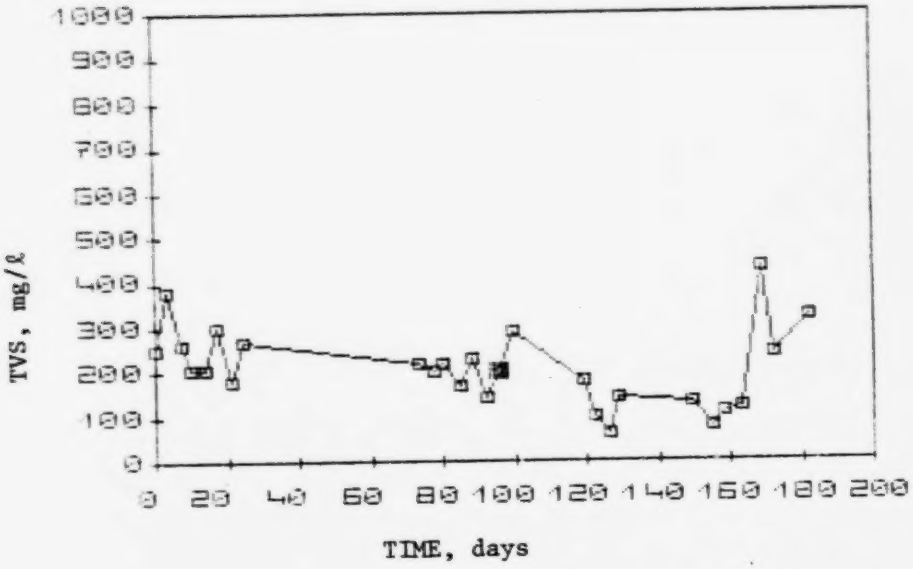

Figure C.257. Total volatile solids concentration of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

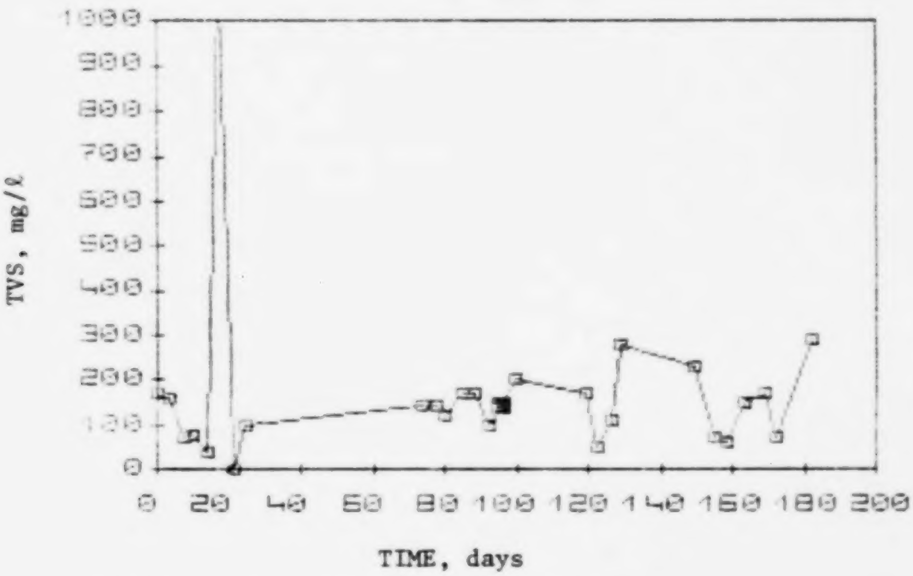

Figure C.258. Total volatile solids concentration of effluent synthetic sewage from the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

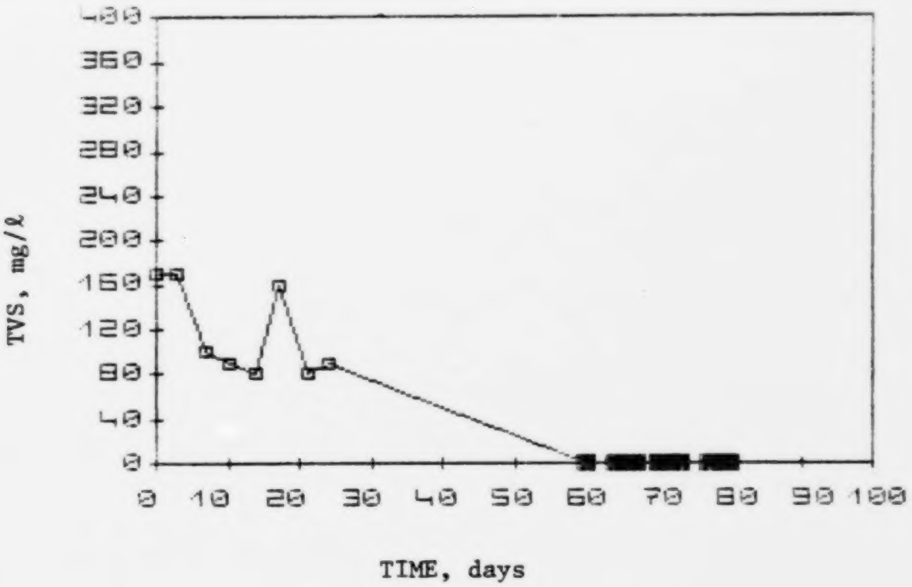

Figure C.259. Total volatile solids concentration of influent synthetic sewage to the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

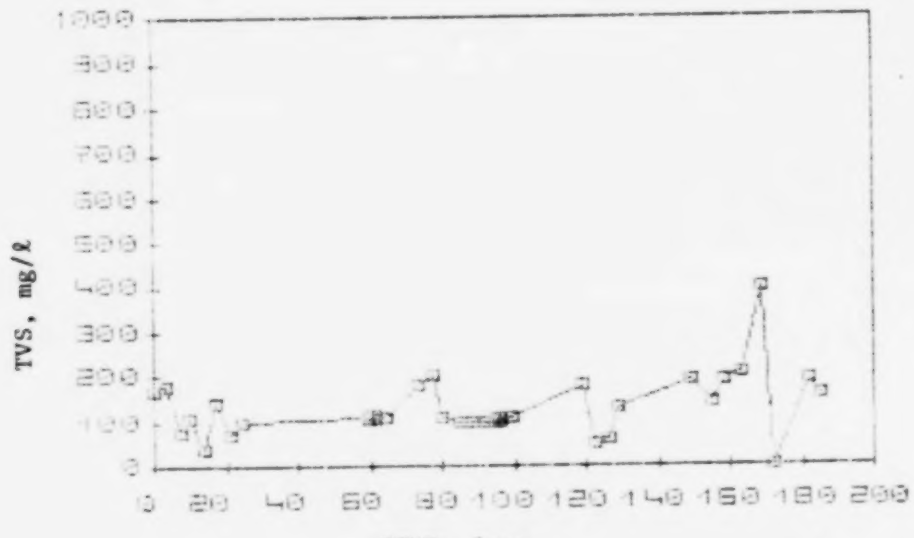

Figure C.260. Total volatile solids concentration of effluent synthetic sewage from the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

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Figure C.261. Total volatile solids concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

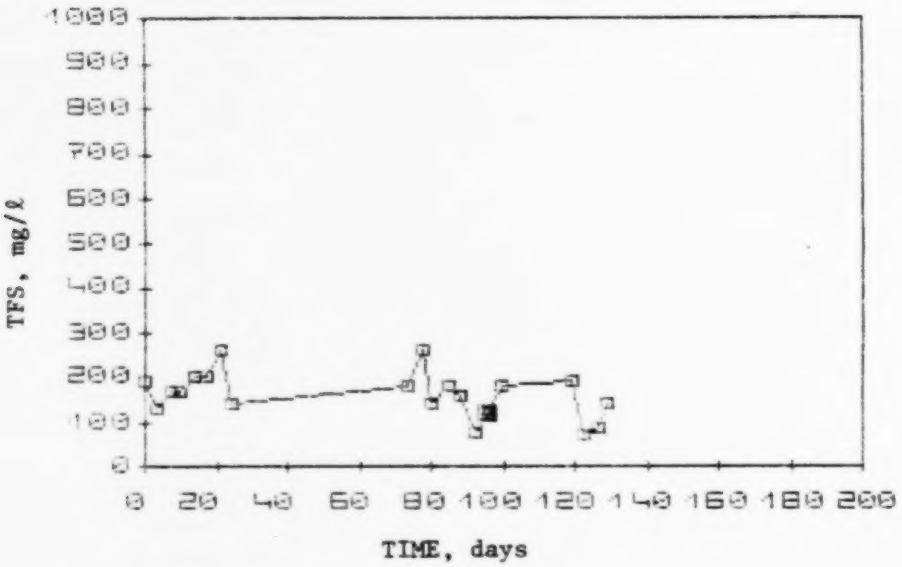


Figure C.262. Total fixed solids concentration of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 1, 1981.

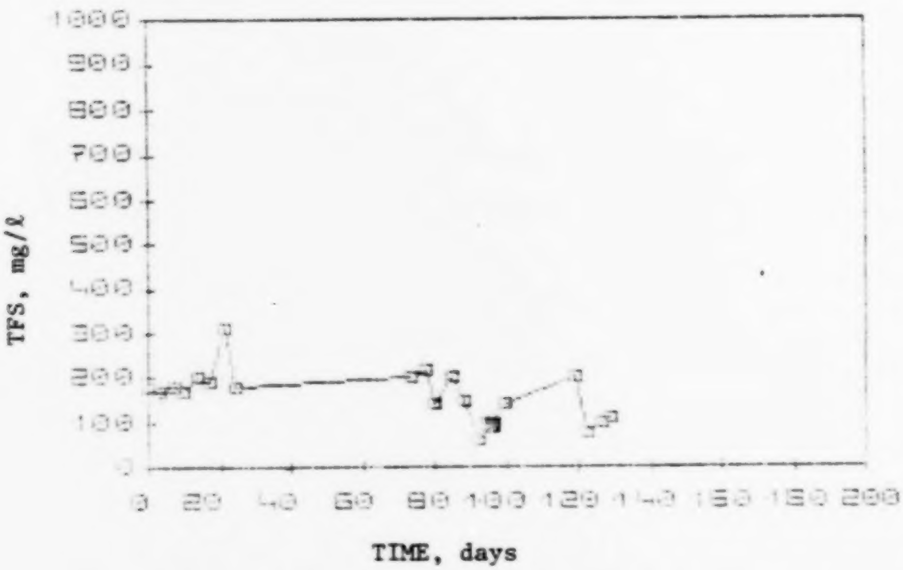


Figure C.263. Total fixed solids concentration of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

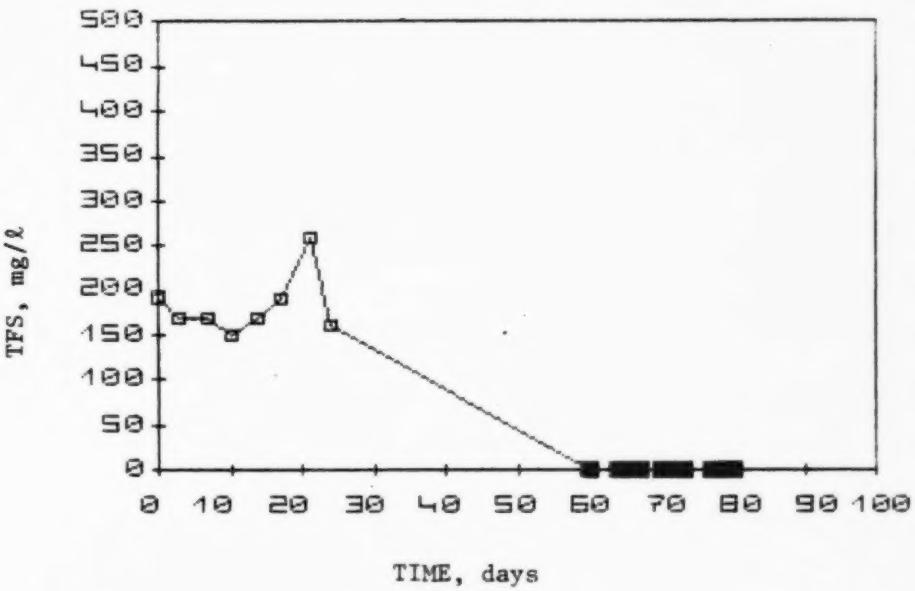


Figure C.264. Total fixed solids concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

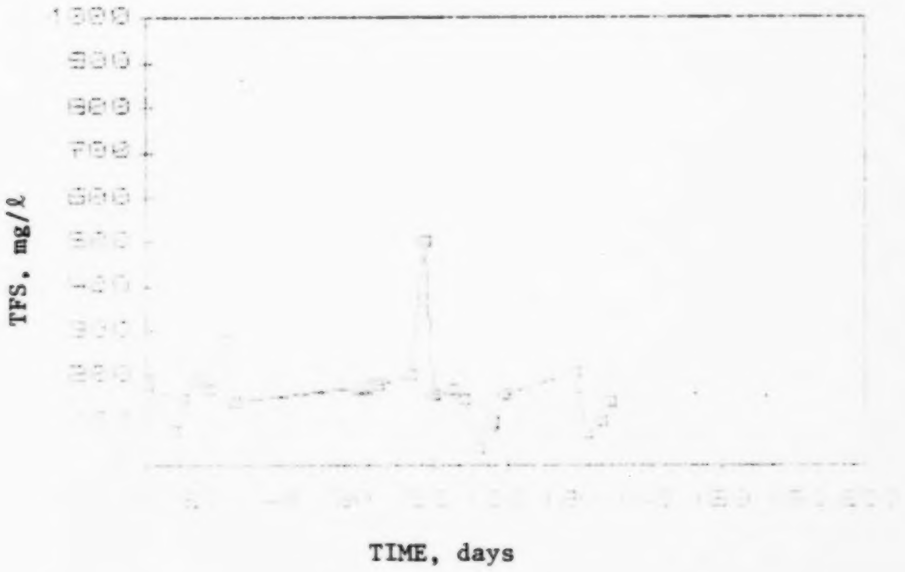


Figure C.265. Total fixed solids concentration of effluent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

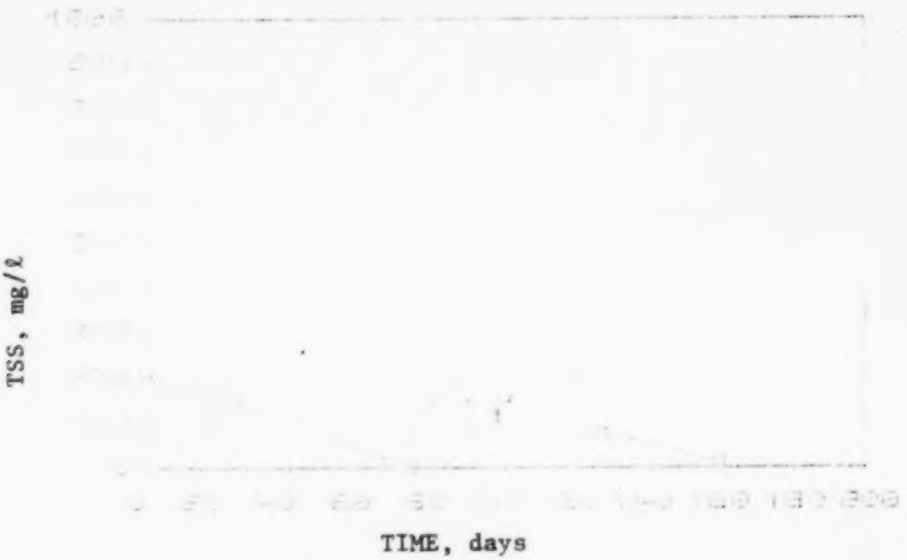


Figure C.266. Total fixed solids concentration of effluent synthetic sewage from the third unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

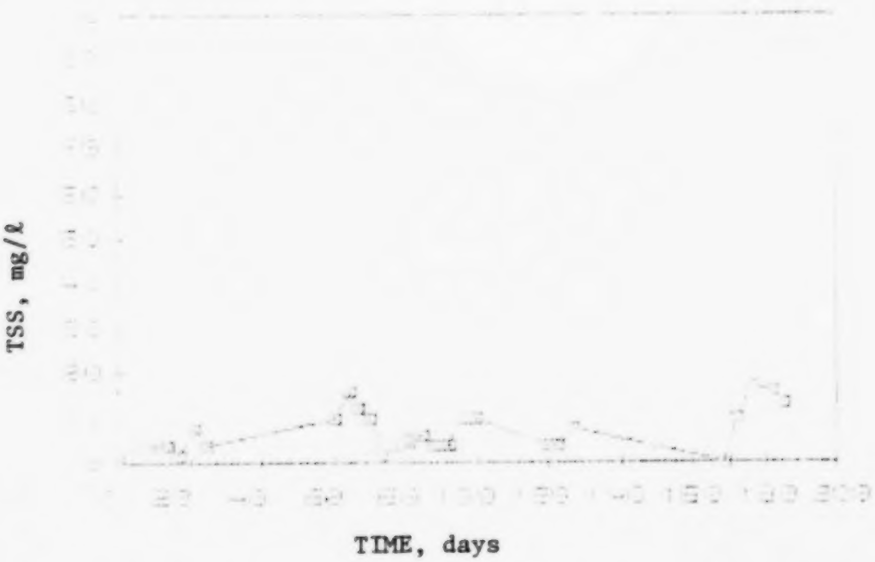


Figure C.267. Total suspended solids concentration of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

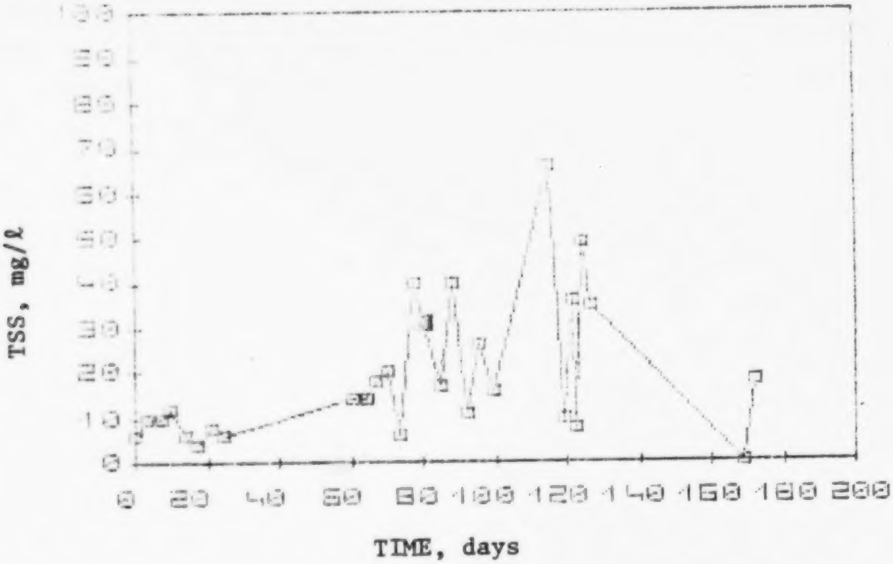


Figure C.268. Total suspended solids concentration of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

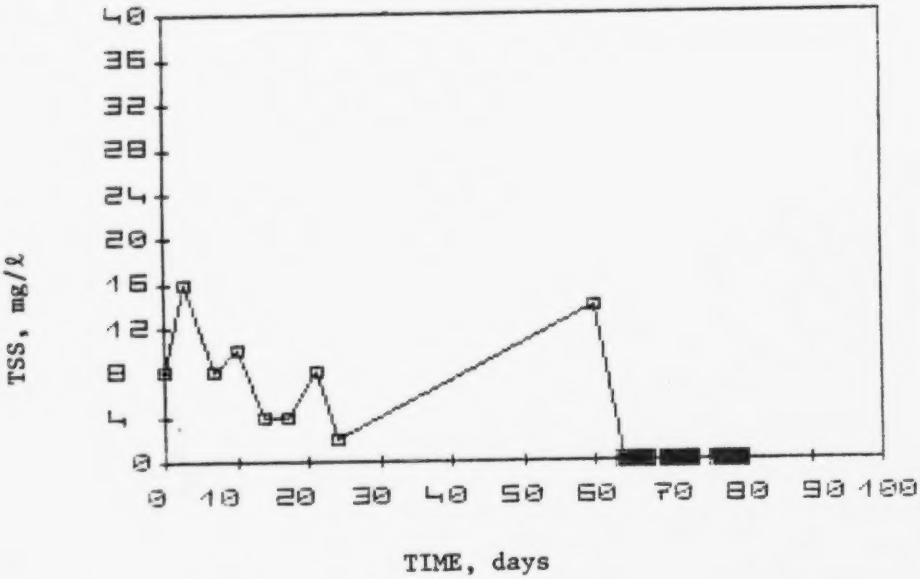


Figure C.269. Total suspended solids concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

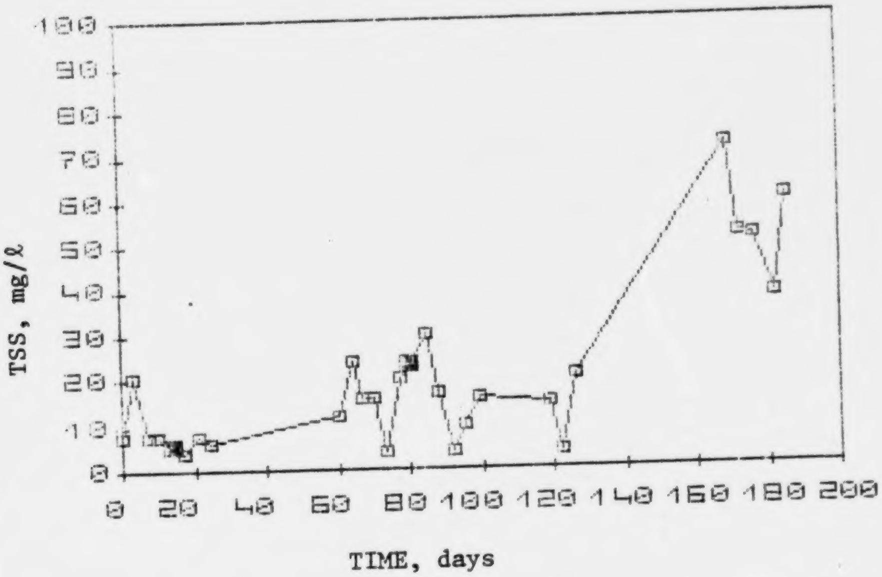


Figure C.270. Total suspended solids concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

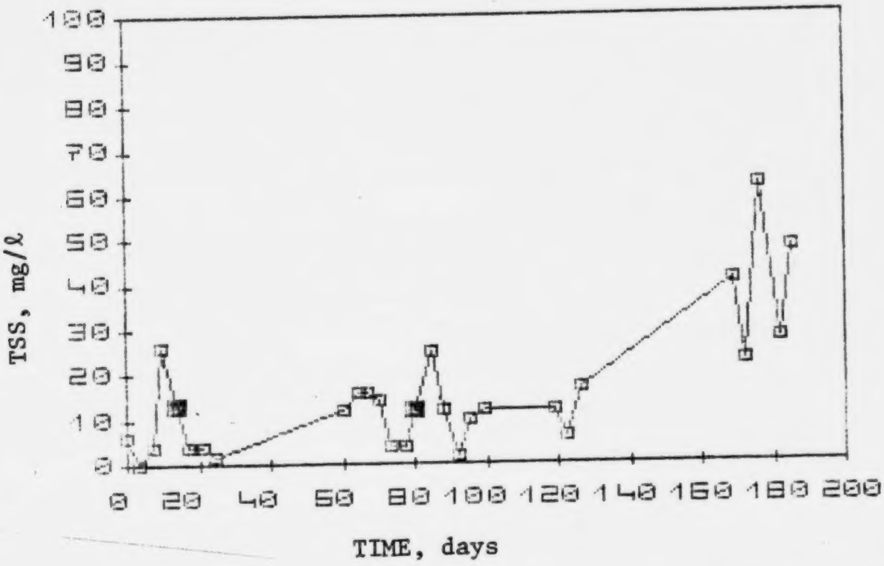


Figure C.271. Total suspended solids concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

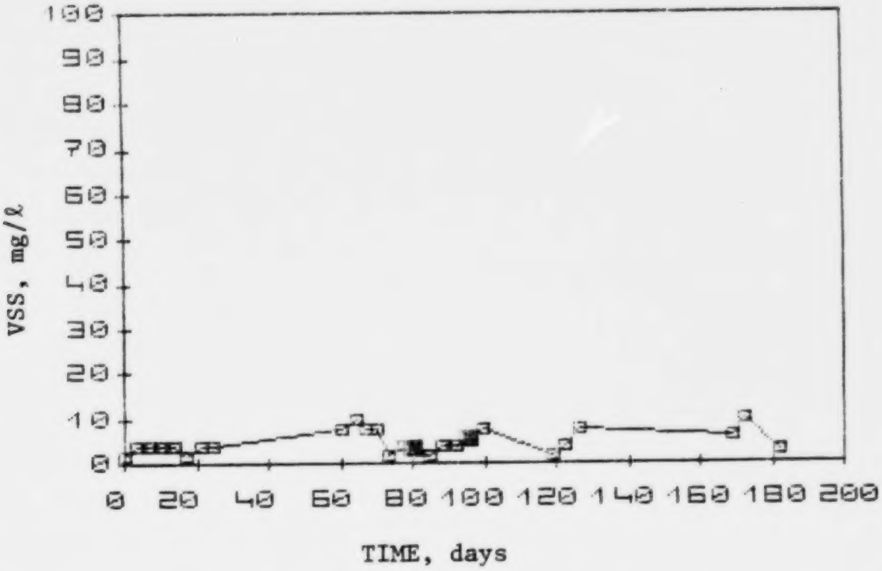


Figure C.272. Volatile suspended solids concentration of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

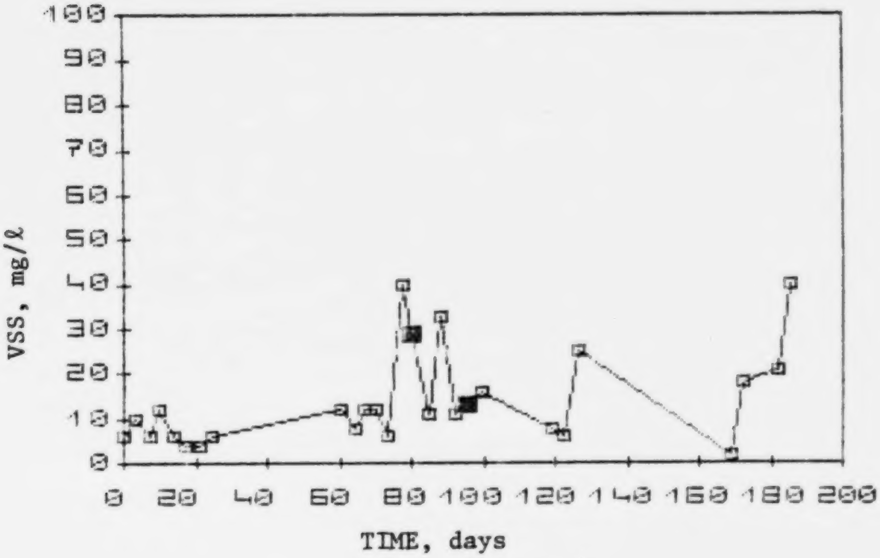


Figure C.273. Volatile suspended solids concentration of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

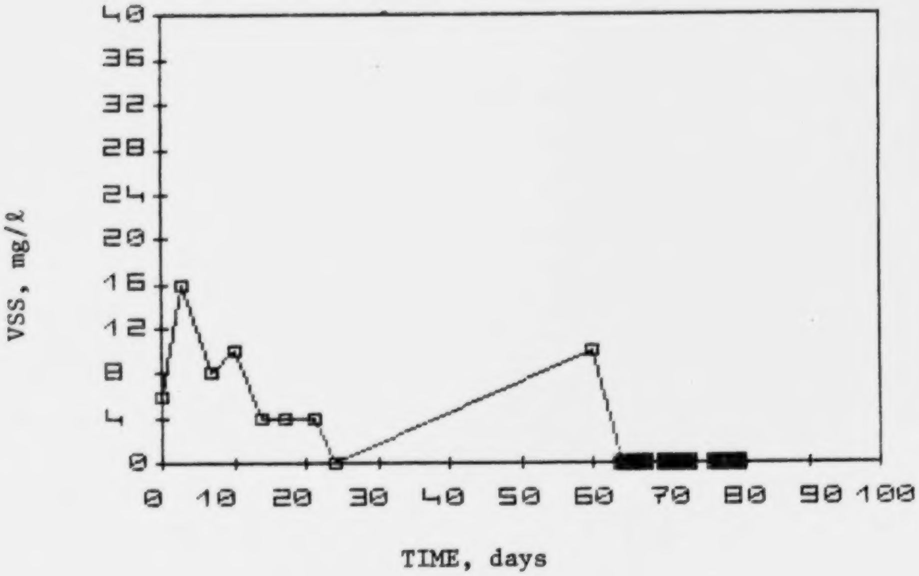


Figure C.274. Volatile suspended solids concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

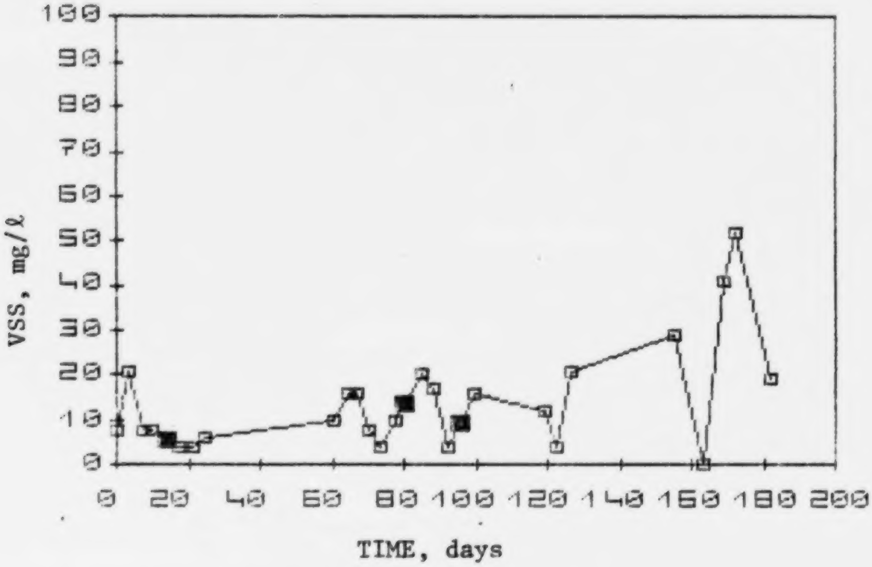


Figure C.275. Volatile suspended solids concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

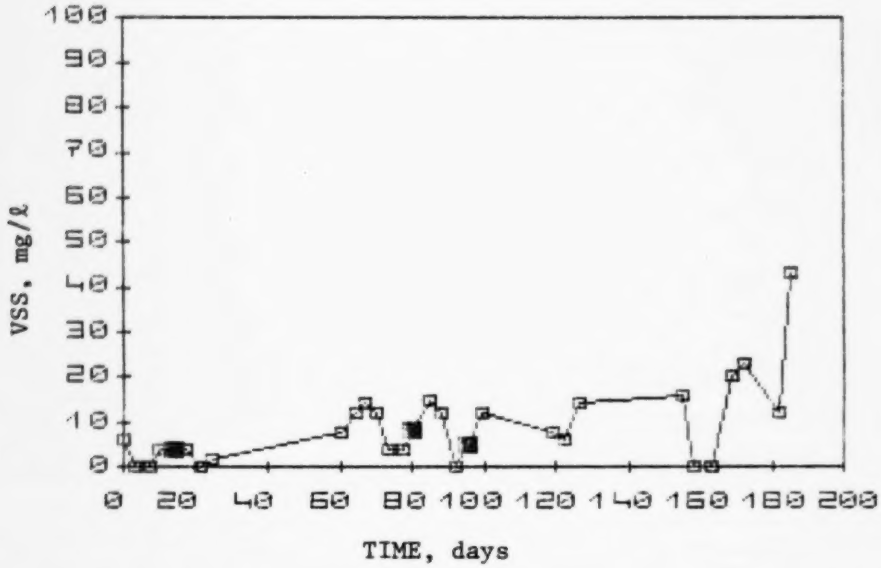


Figure C.276. Volatile suspended solids concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

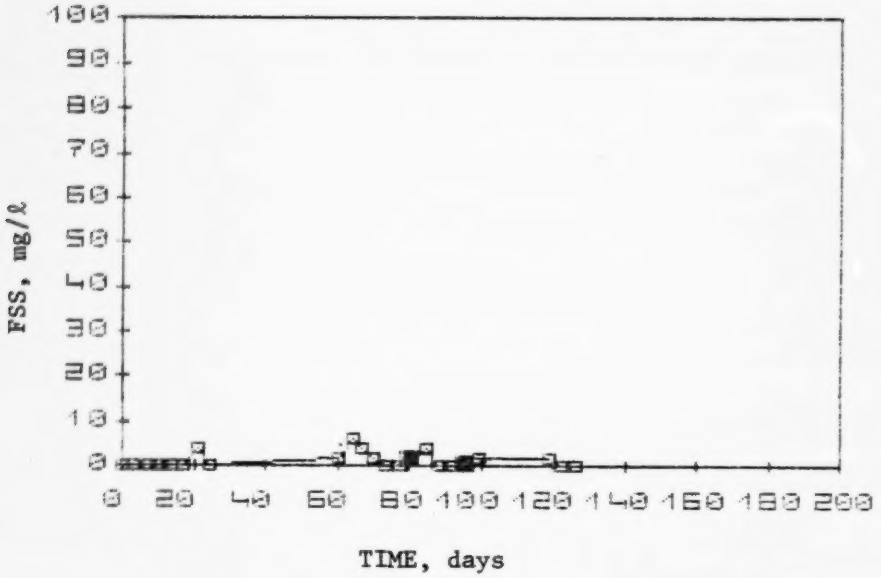


Figure C.277. Fixed suspended solids concentration of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

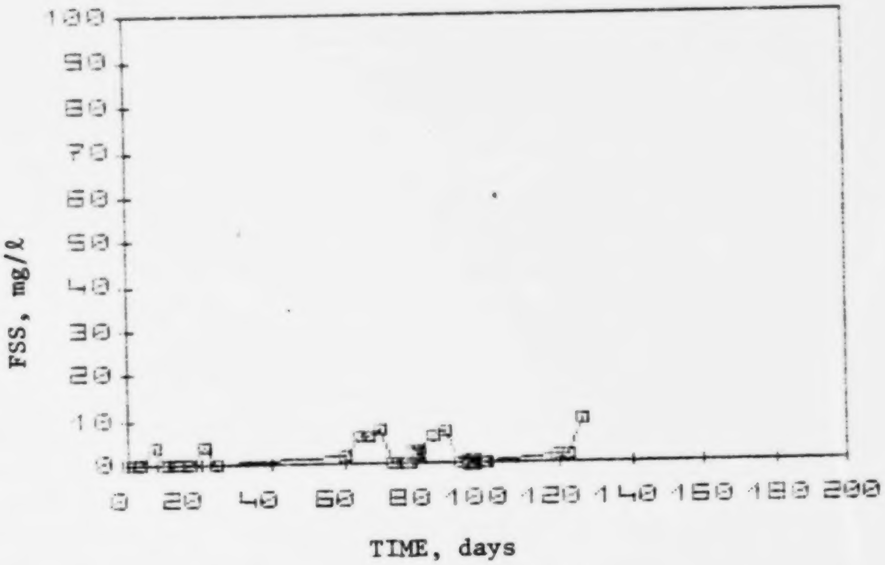


Figure C.278. Fixed suspended solids concentration of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

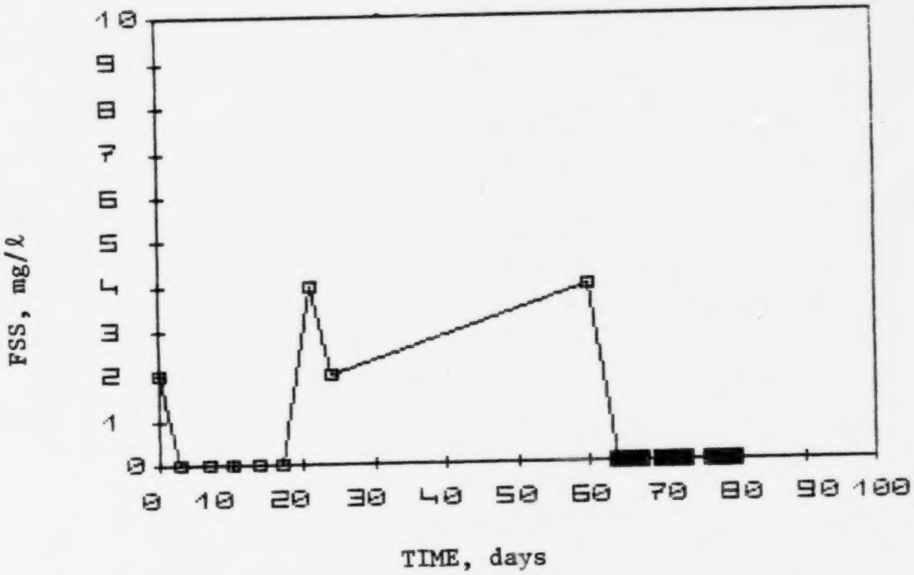


Figure C.279. Fixed suspended solids concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

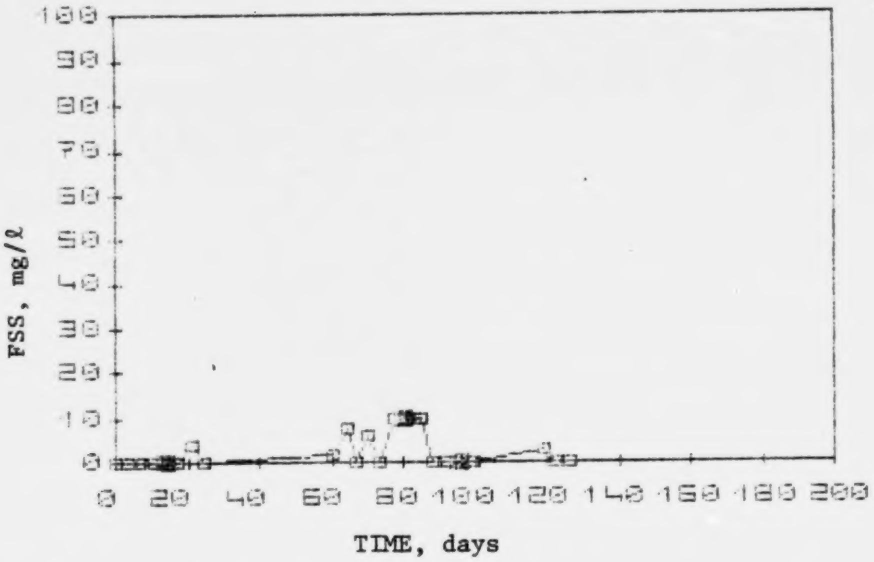


Figure C.280. Fixed suspended solids concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

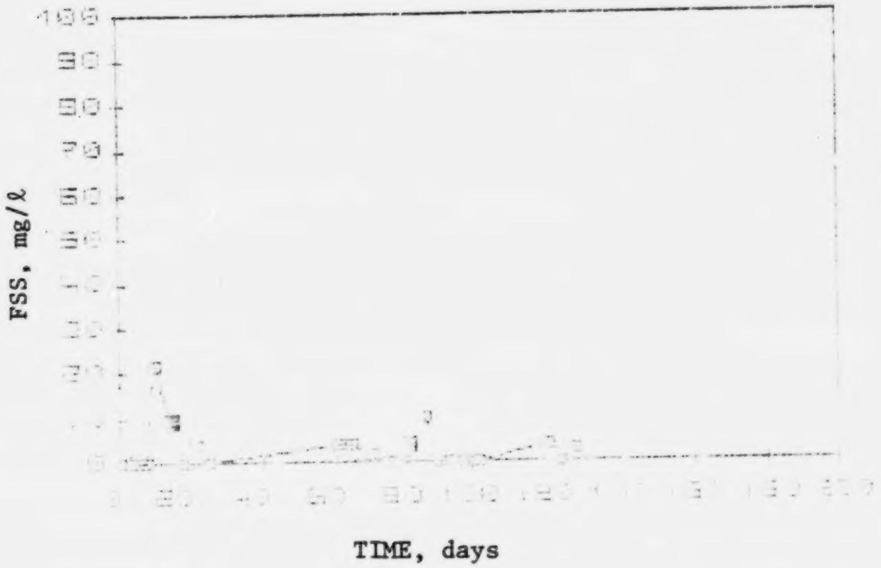


Figure C.281. Fixed suspended solids concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

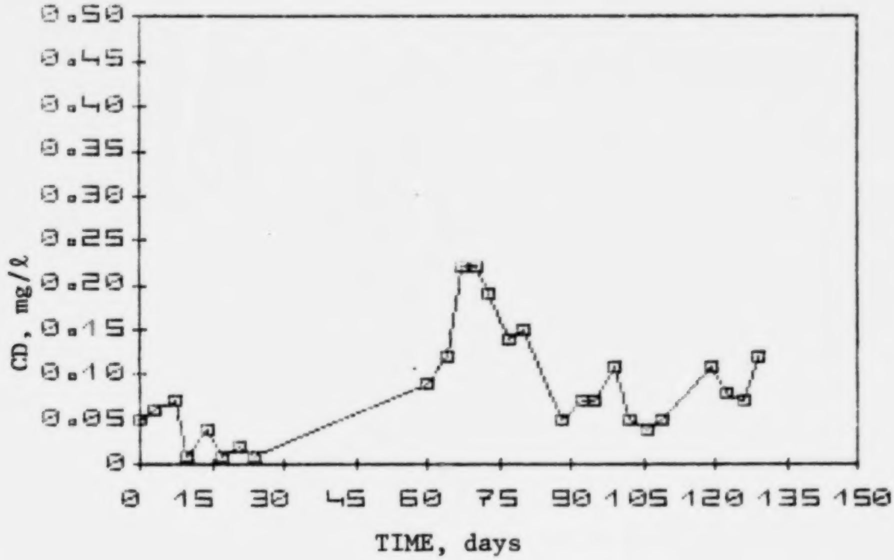


Figure C.282. Cadmium concentration of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

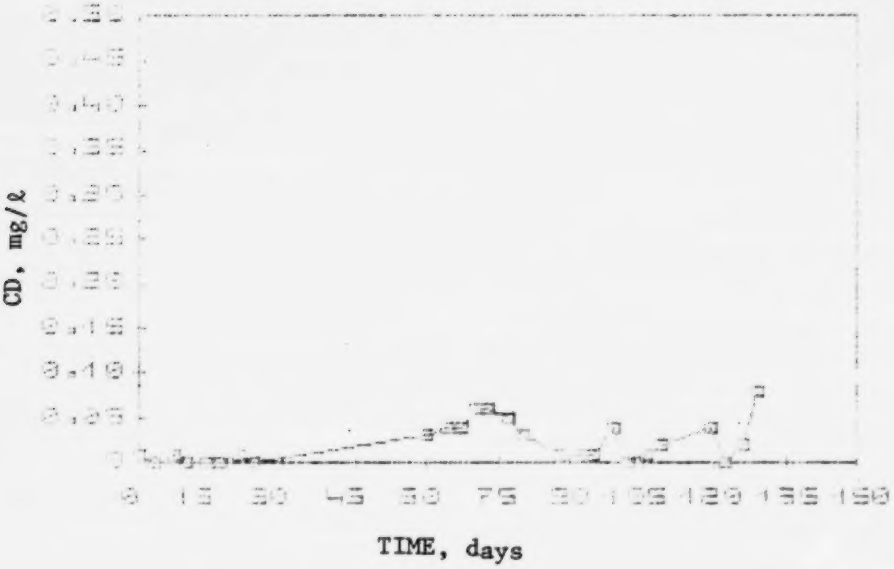


Figure C.283. Cadmium concentration of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

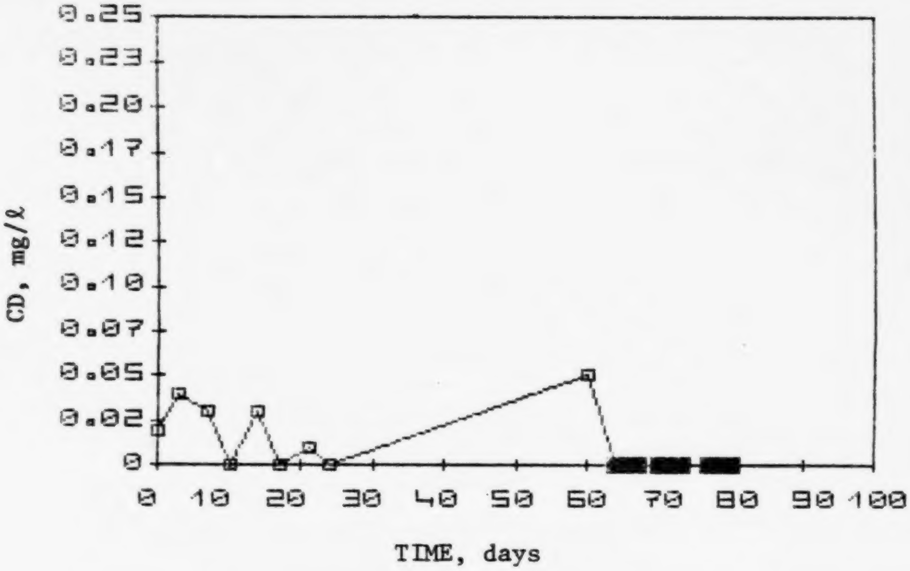


Figure C.284. Cadmium concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

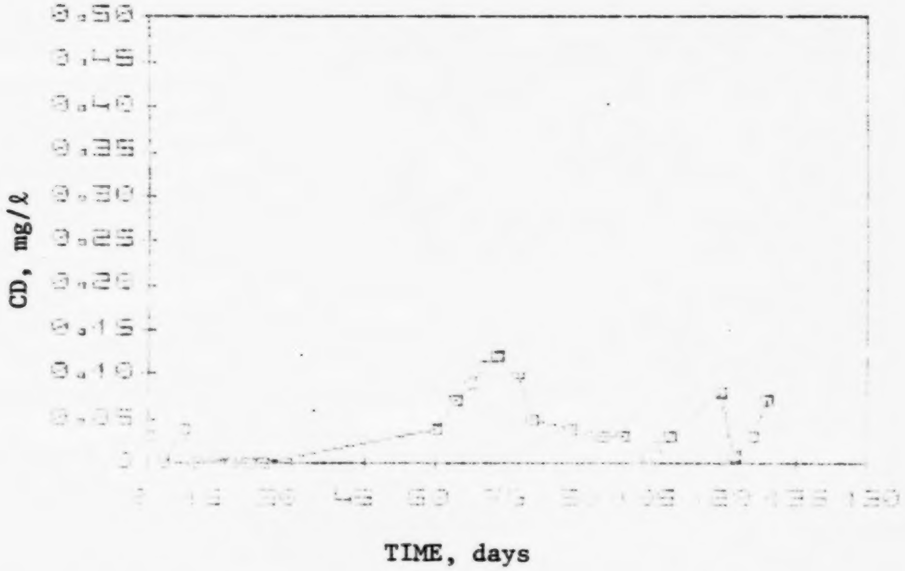


Figure C.285. Cadmium concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

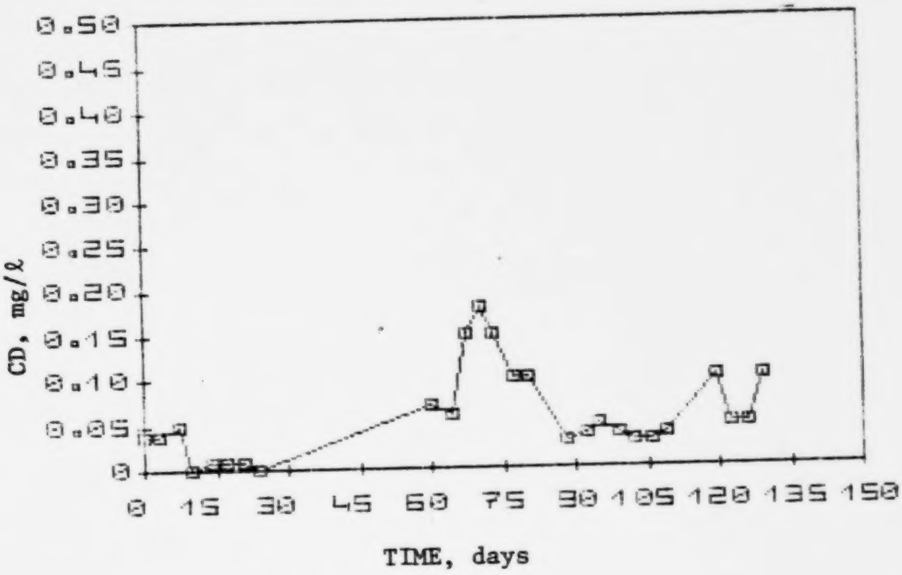


Figure C.286. Cadmium concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

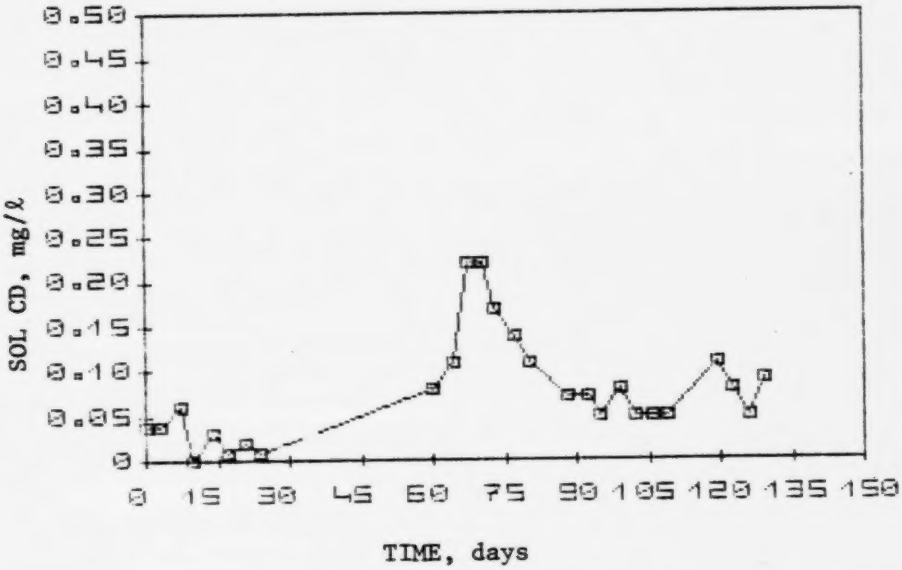


Figure C.287. Soluble cadmium concentration of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

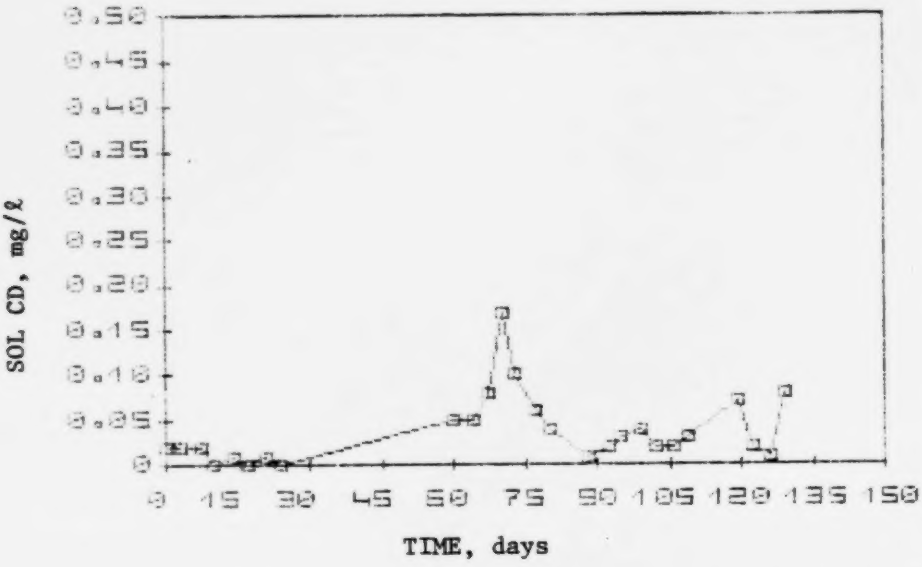


Figure C.288. Soluble cadmium concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

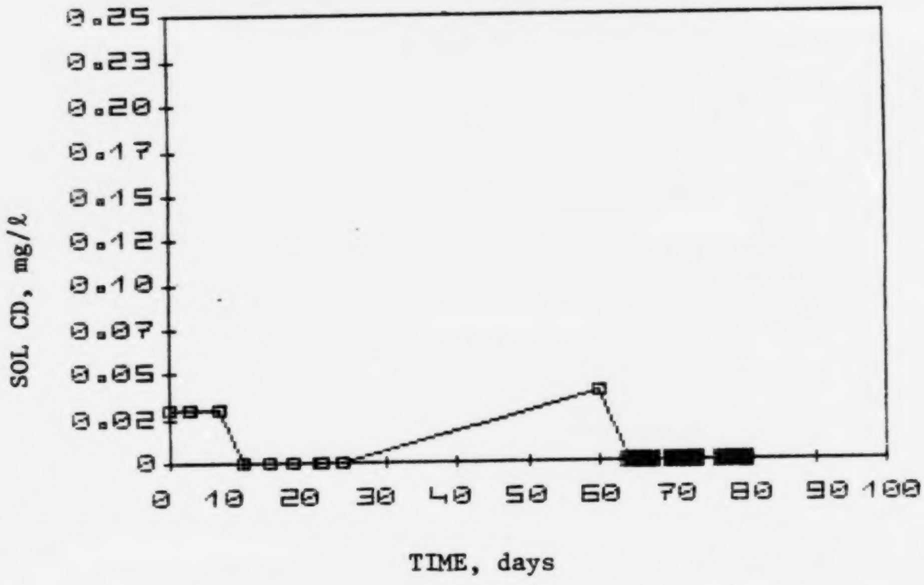


Figure C.289. Soluble cadmium concentration of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

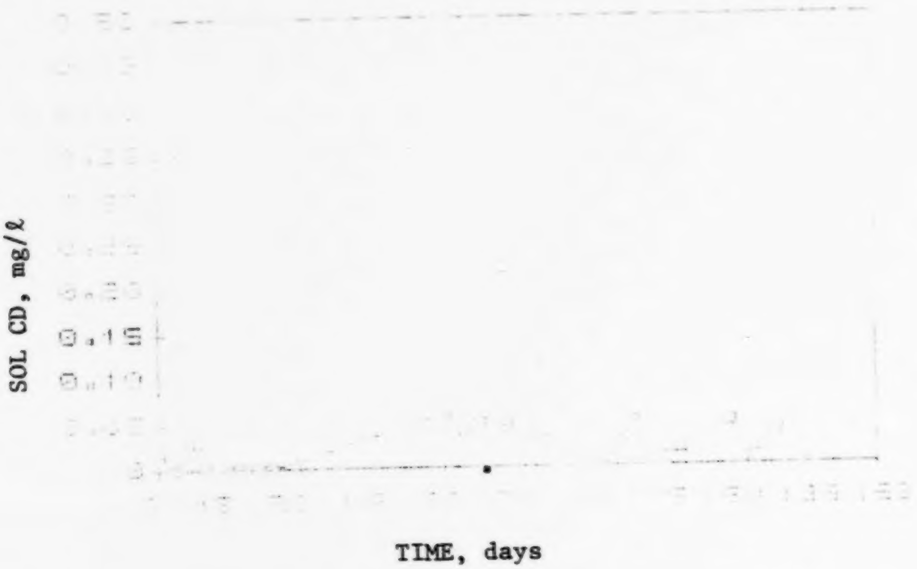


Figure C.290. Soluble cadmium concentration of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

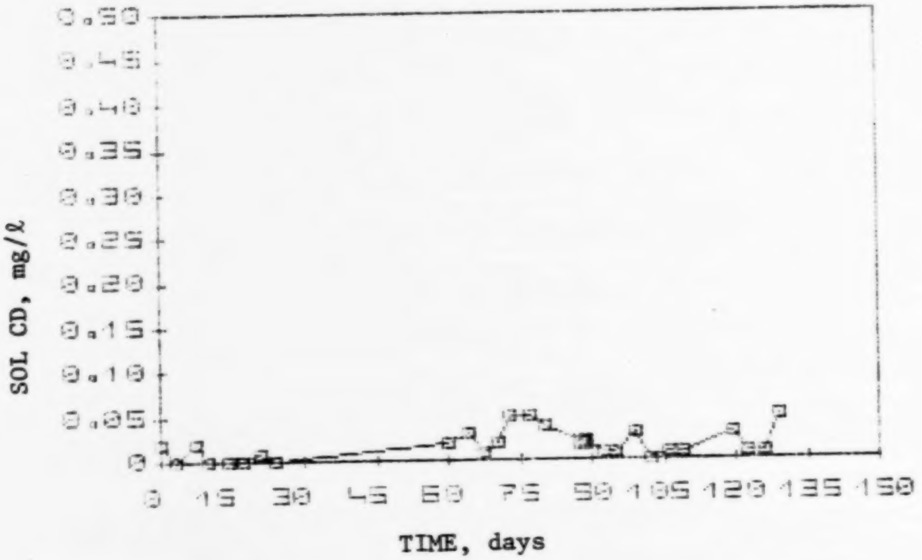
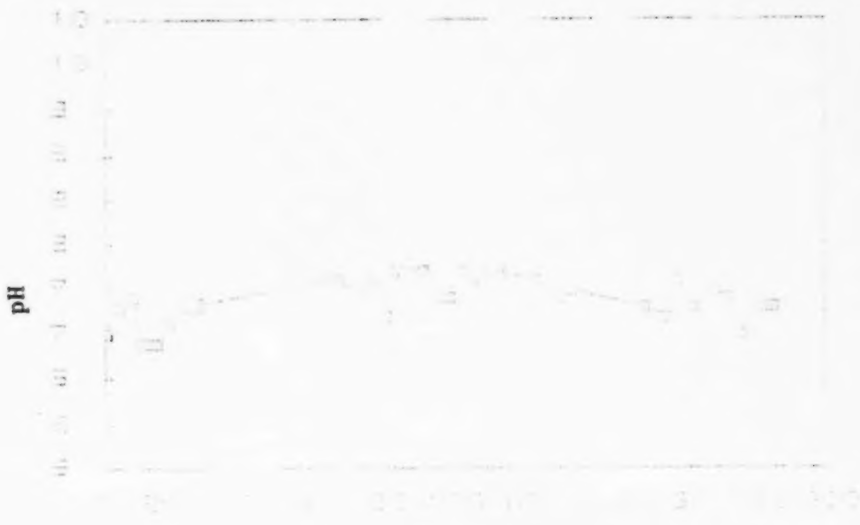
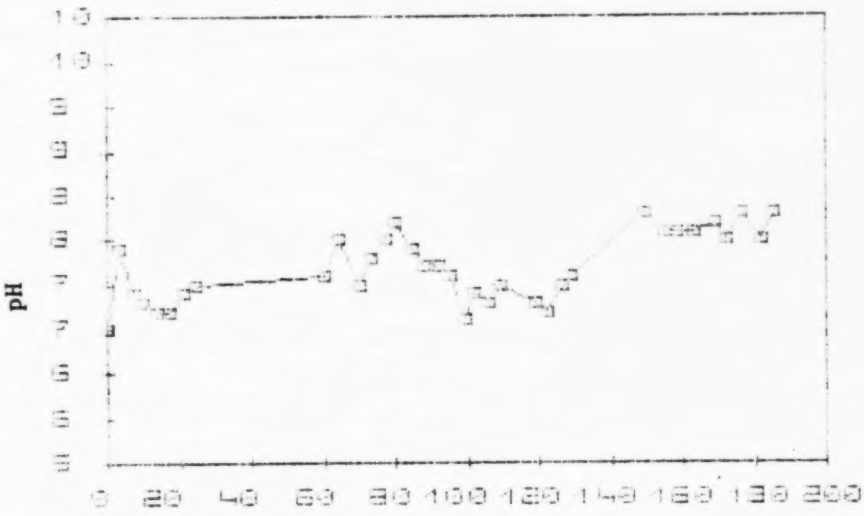


Figure C.291. Soluble cadmium concentration of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.



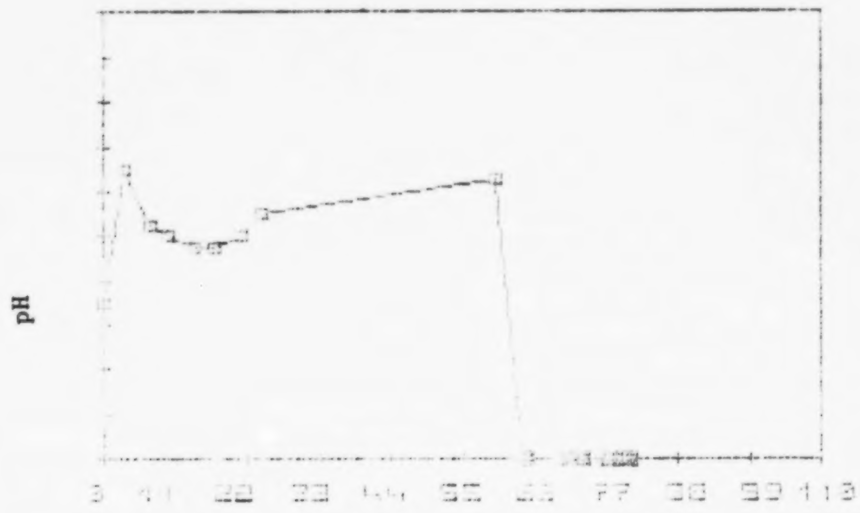
TIME, days

Figure C.292. pH of influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.



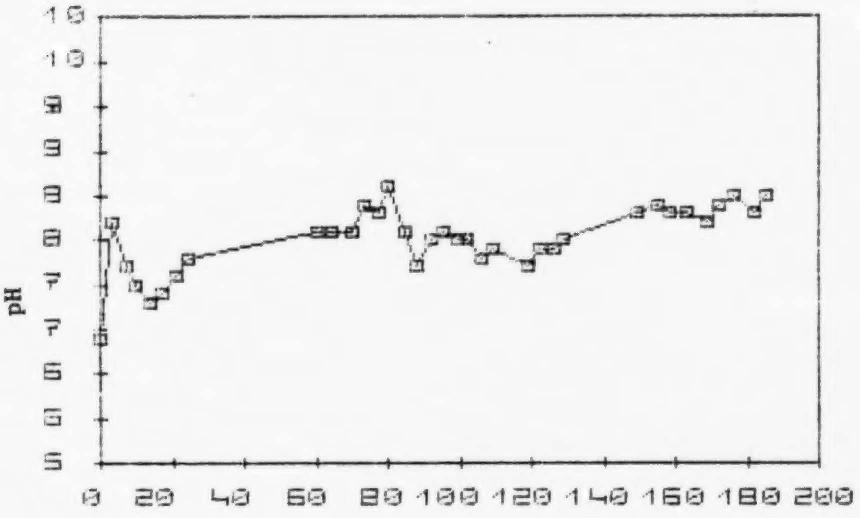
TIME, days

Figure C.293. pH of effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.



TIME, days

Figure C.294. pH of influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.



TIME, days

Figure C.295. pH of effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

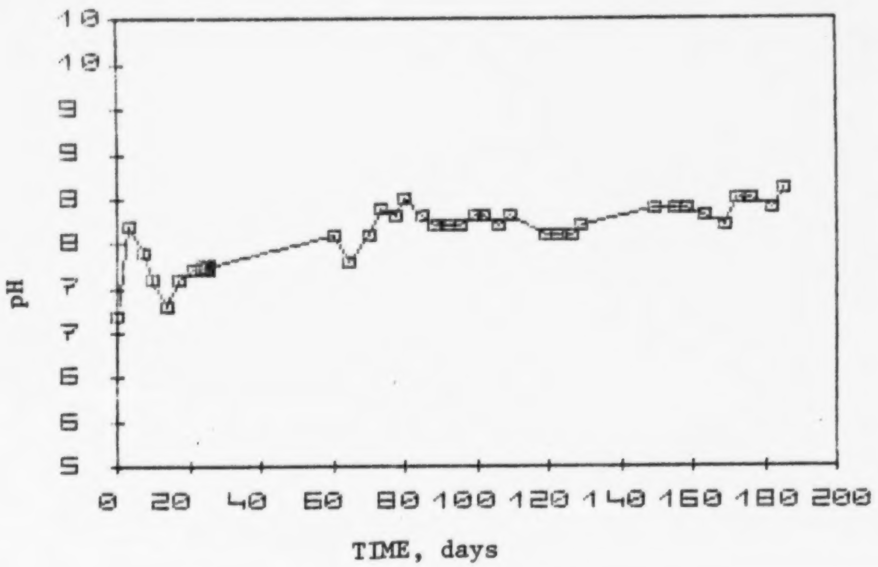


Figure C.296. pH of effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

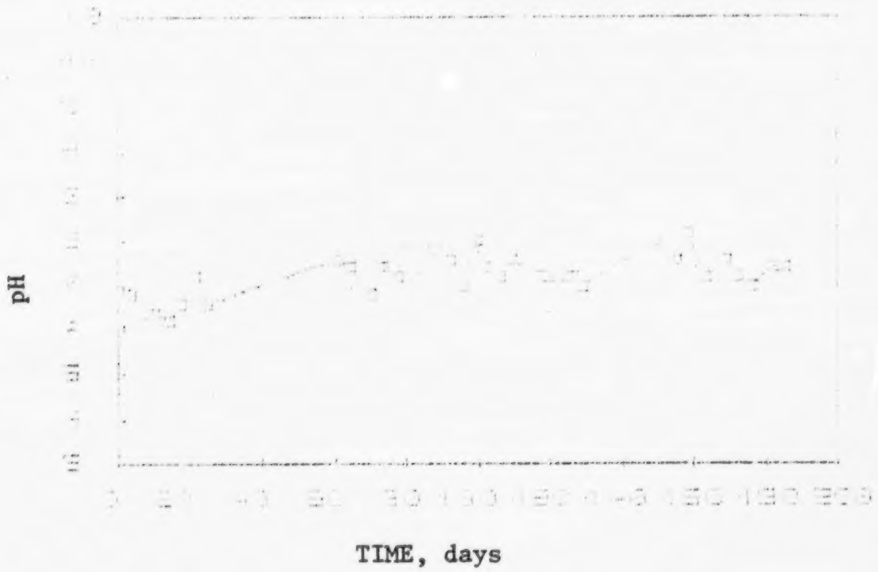


Figure C.297. pH of filtered influent synthetic sewage to the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

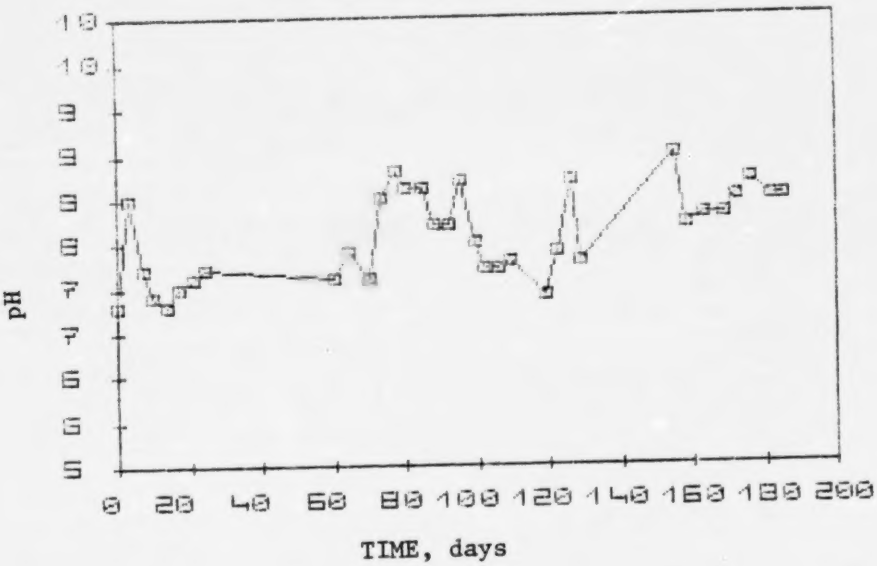


Figure C.298. pH of filtered effluent synthetic sewage from the first unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

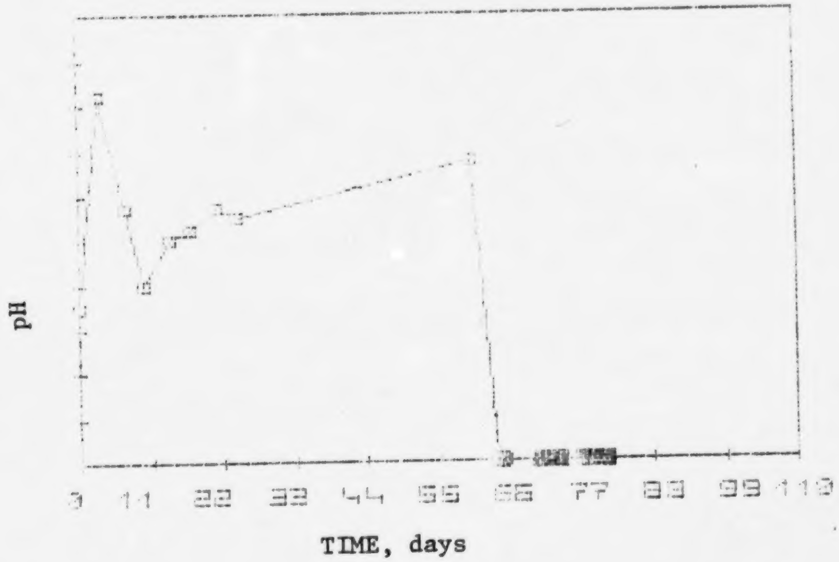


Figure C.299. pH of filtered influent synthetic sewage to the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

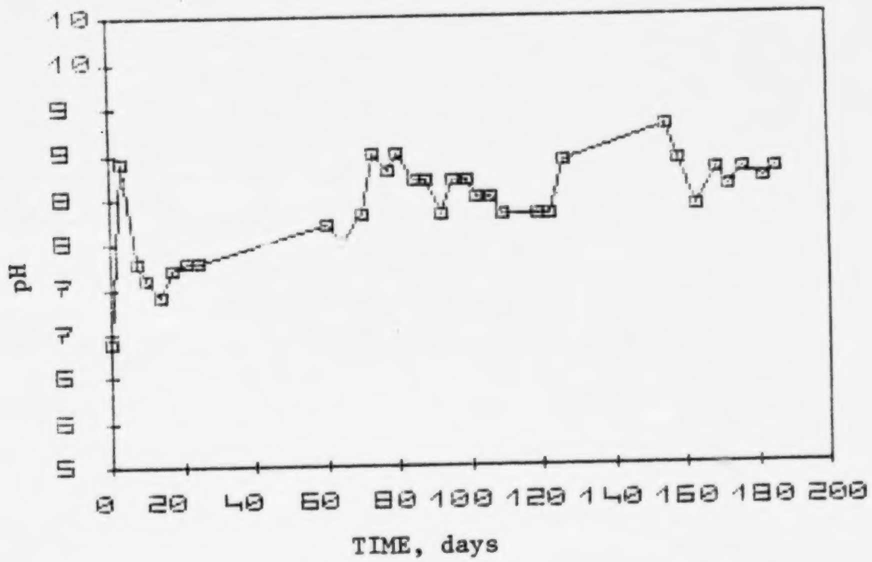


Figure C.300. pH of filtered effluent synthetic sewage from the second unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

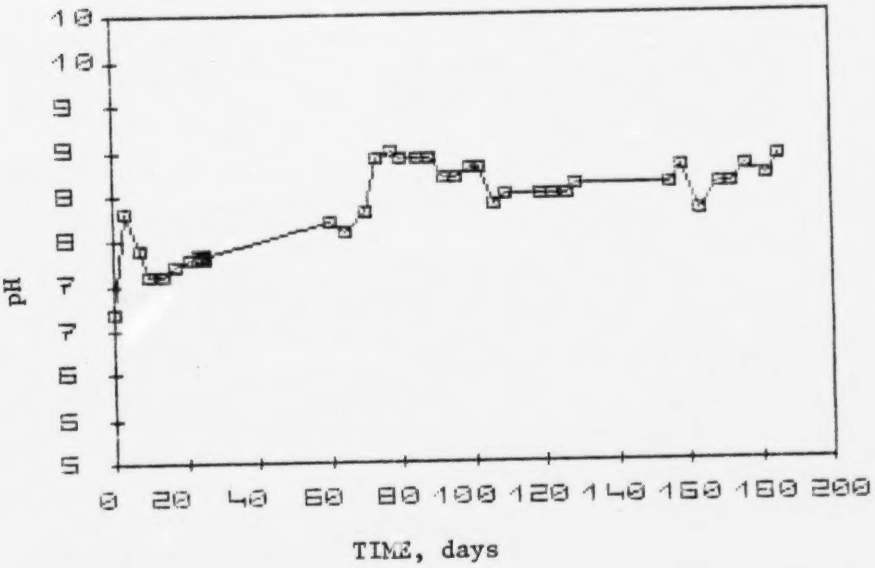


Figure C.301. pH of filtered effluent synthetic sewage from the third unit in the three unit Cornell NFT system in Phase 1. First day of analysis was February 16, 1981.

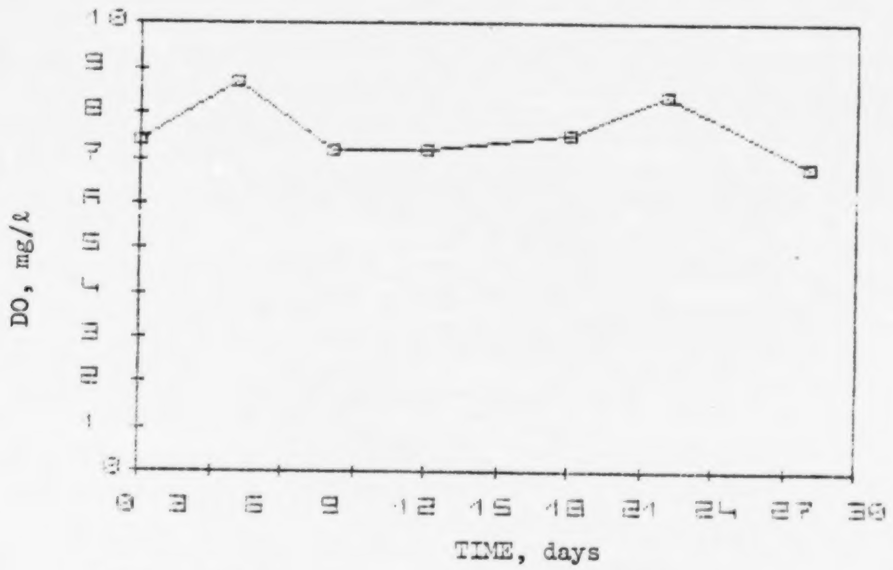


Figure C.302. Dissolved oxygen concentration of influent sewage delivered to the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1981.

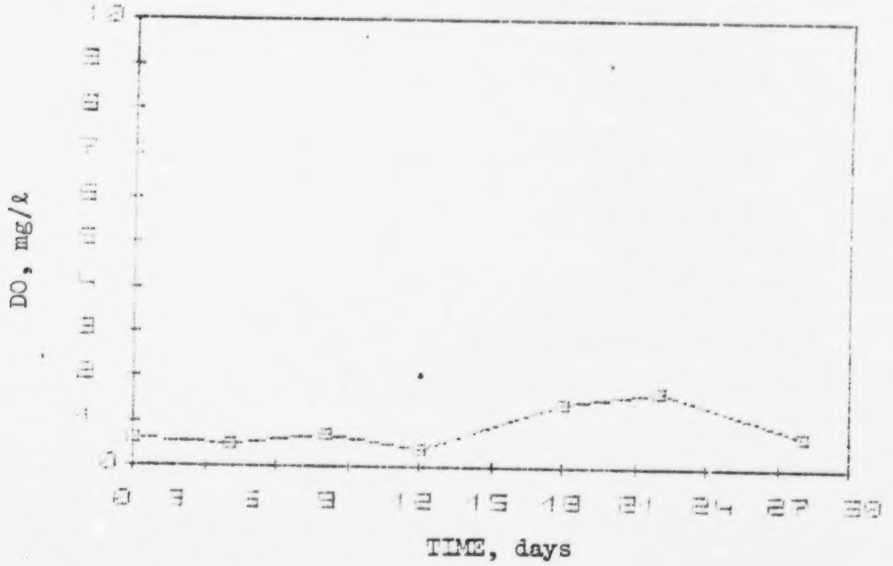


Figure C.303. Dissolved oxygen concentration of influent synthetic sewage at Point A of the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1981.

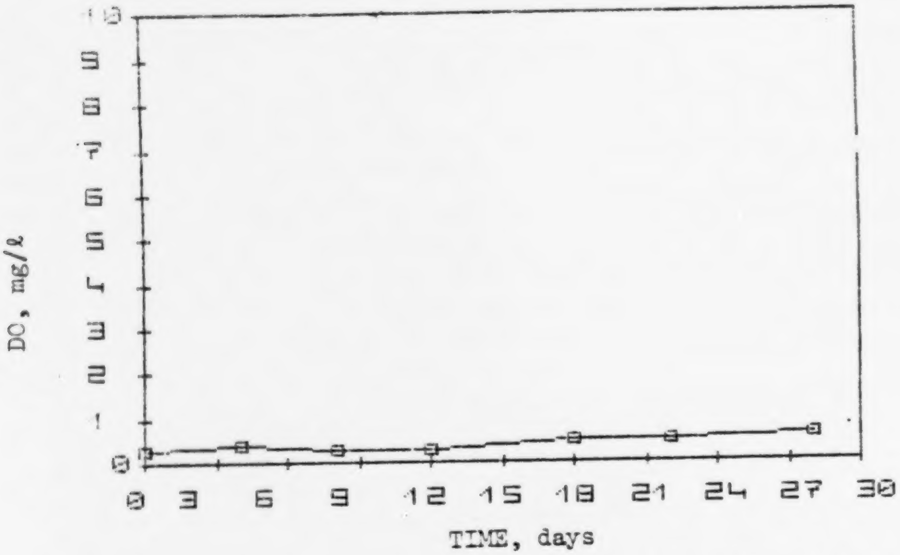


Figure C.304. Dissolved oxygen concentration of influent synthetic sewage at Point B of the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1981.

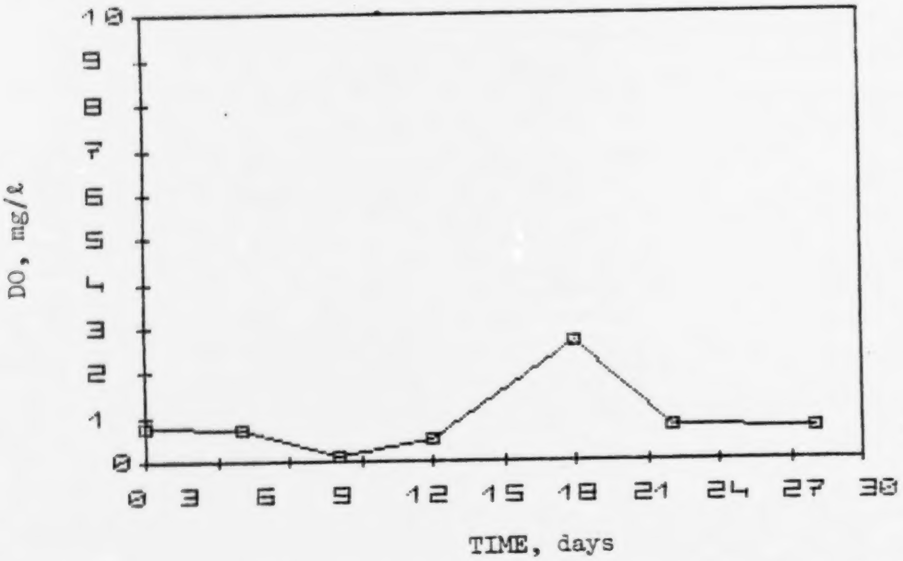


Figure C.305. Dissolved oxygen concentration of effluent synthetic sewage from the first unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1981.

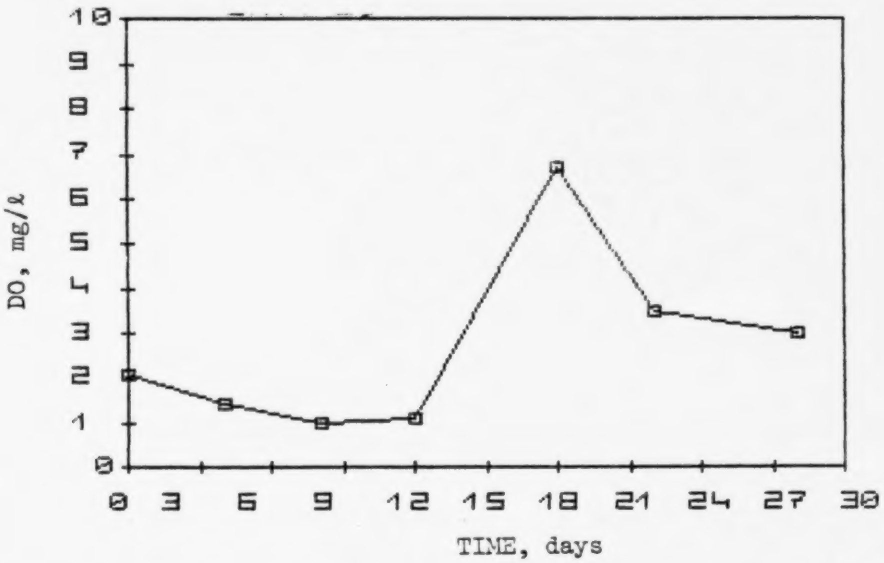


Figure C.306. Dissolved oxygen concentration of influent synthetic sewage to the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1981.

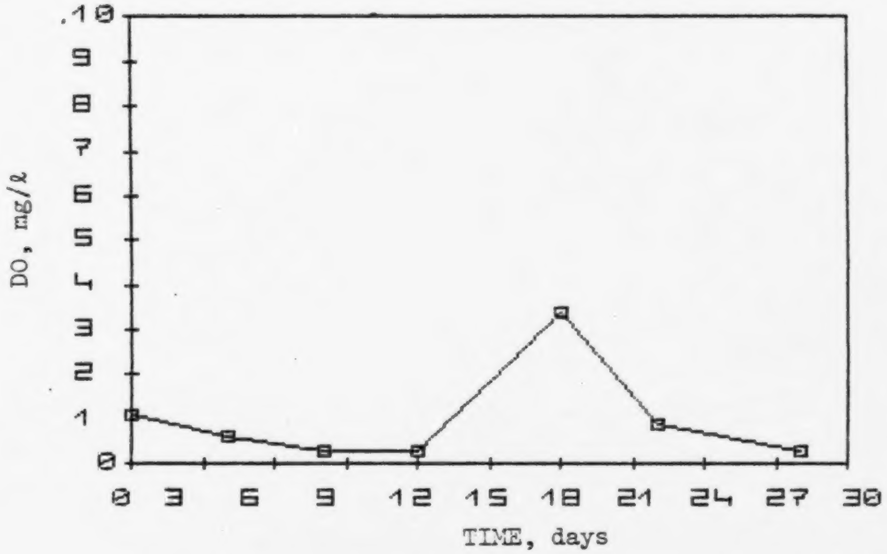


Figure C.307. Dissolved oxygen concentration of influent synthetic sewage at Point A of the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1981.

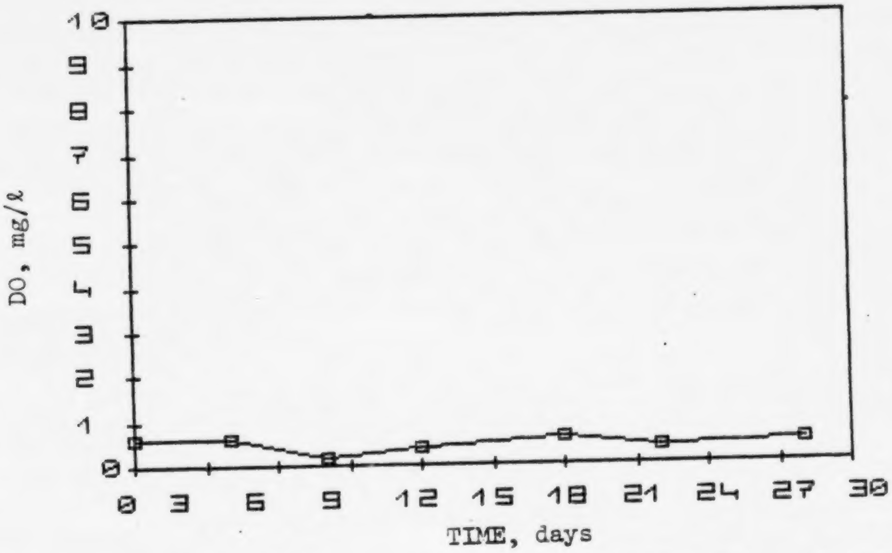


Figure C.308. Dissolved oxygen concentration of influent synthetic sewage at Point B of the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1981.

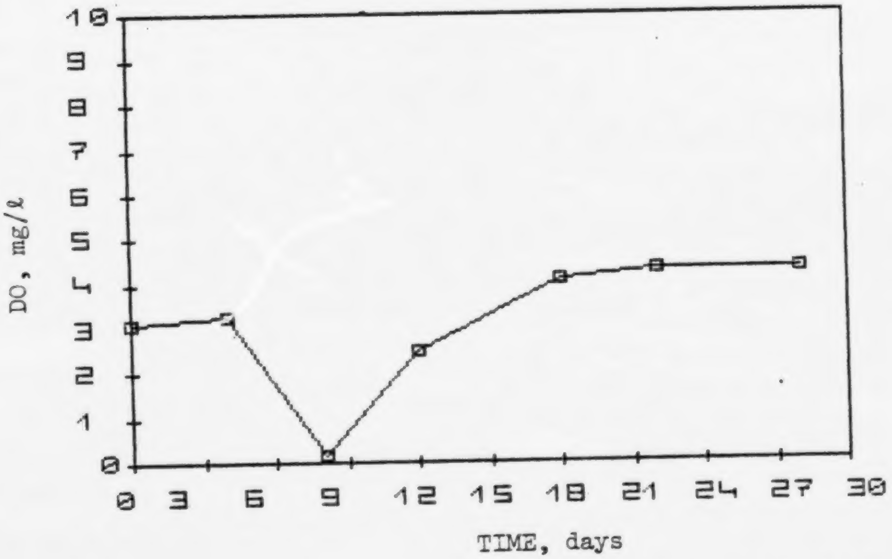


Figure C.309. Dissolved oxygen concentration of effluent synthetic sewage from the second unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1981.

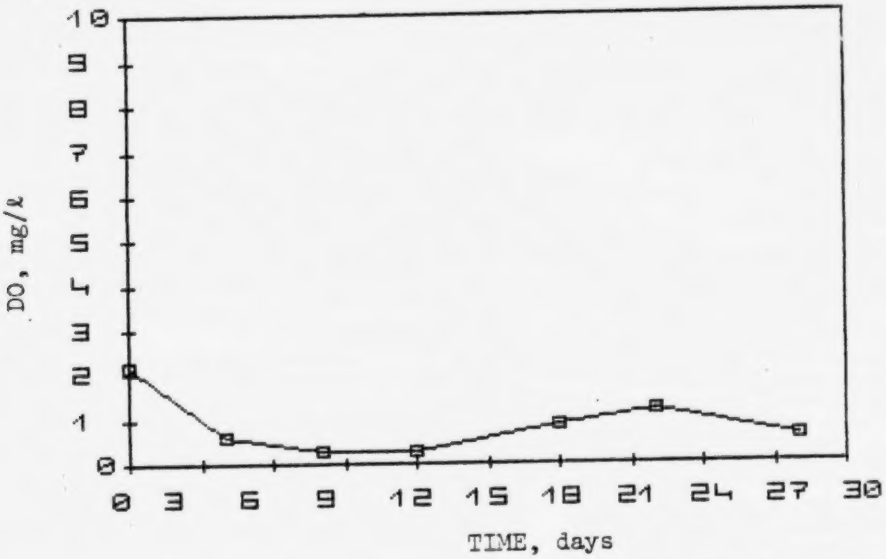


Figure C.310. Dissolved oxygen concentration of influent synthetic sewage to the third uhit of the the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1980.

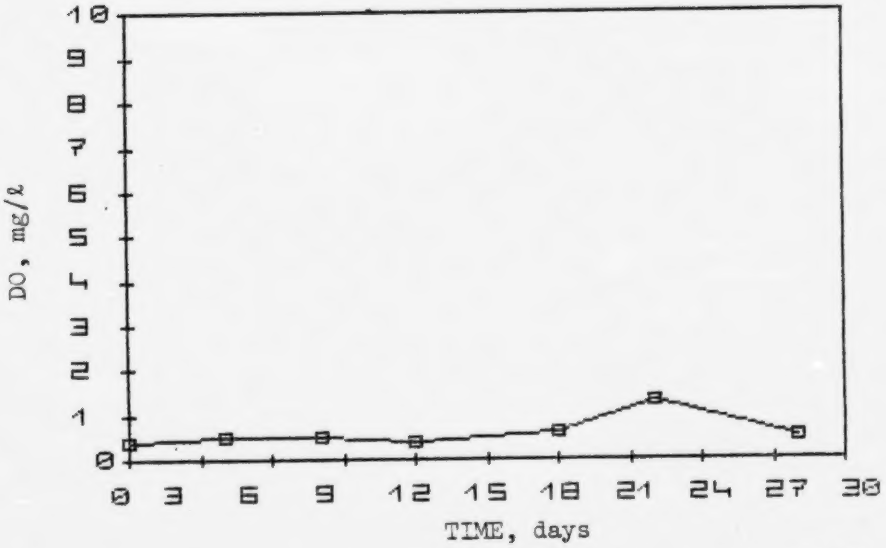


Figure C.311. Dissolved oxygen concentration of influent synthetic sewage at Point A of the third unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1980.

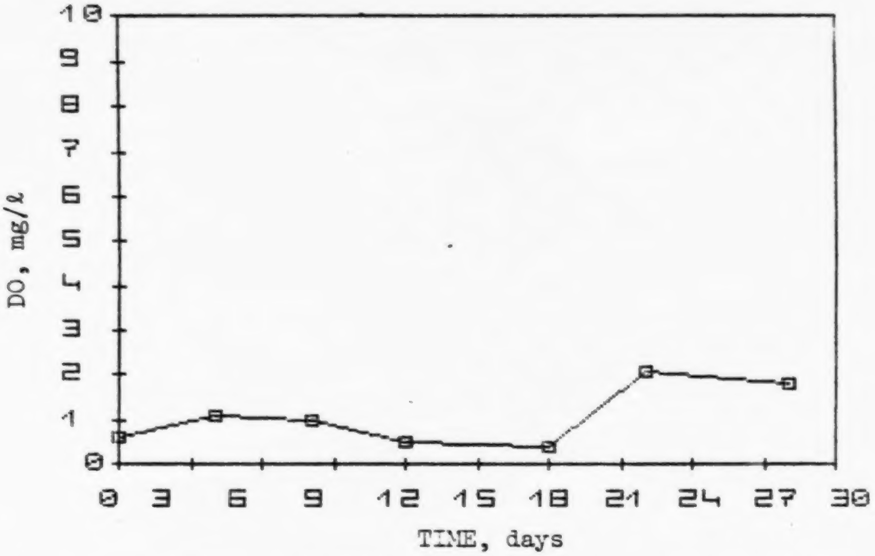


Figure C.312. Dissolved oxygen concentration of influent synthetic sewage at Point B of the third unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1981.

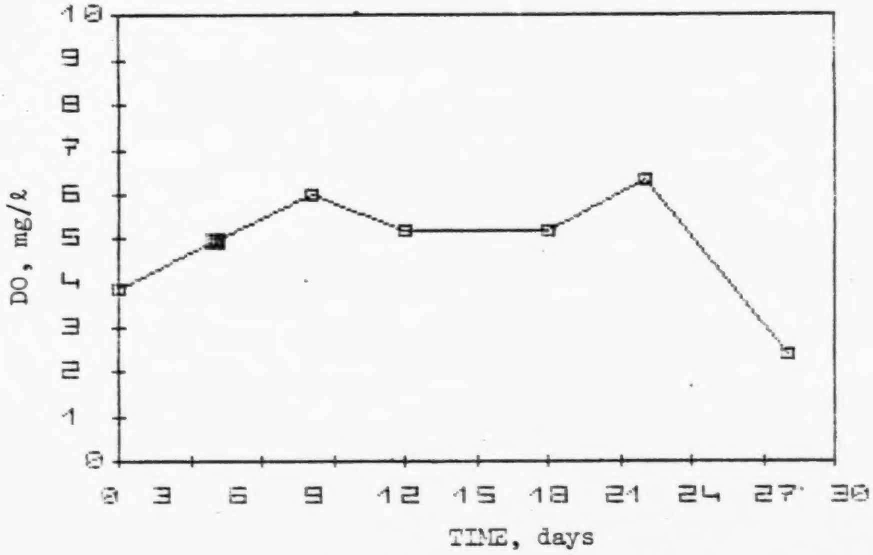


Figure C.313. Dissolved oxygen concentration of effluent synthetic sewage from the third unit of the three unit Cornell NFT system in Phase 1. First day of analysis was February 19, 1981.

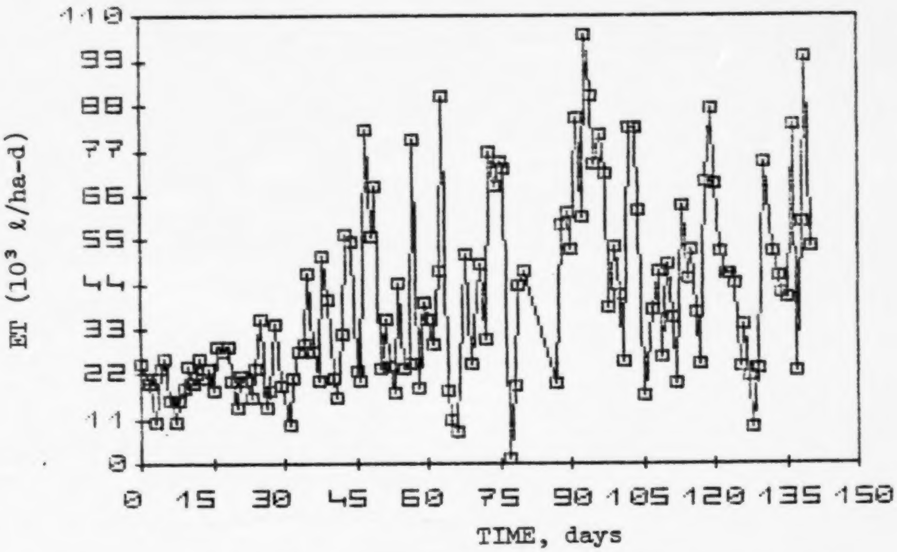


Figure C.314. Evapotranspiration from the three unit Cornell NFT system in Phase 1. First day of measurement was February 17, 1981.

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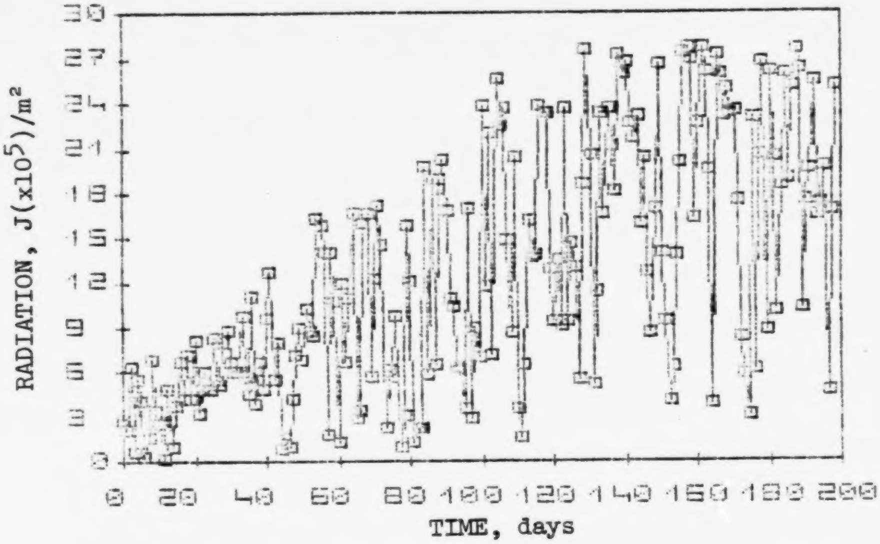

Figure C.315. Incident solar radiation at Ithaca, NY, over the Cornell NFT experimental period. First day of measurement was October 1, 1979.

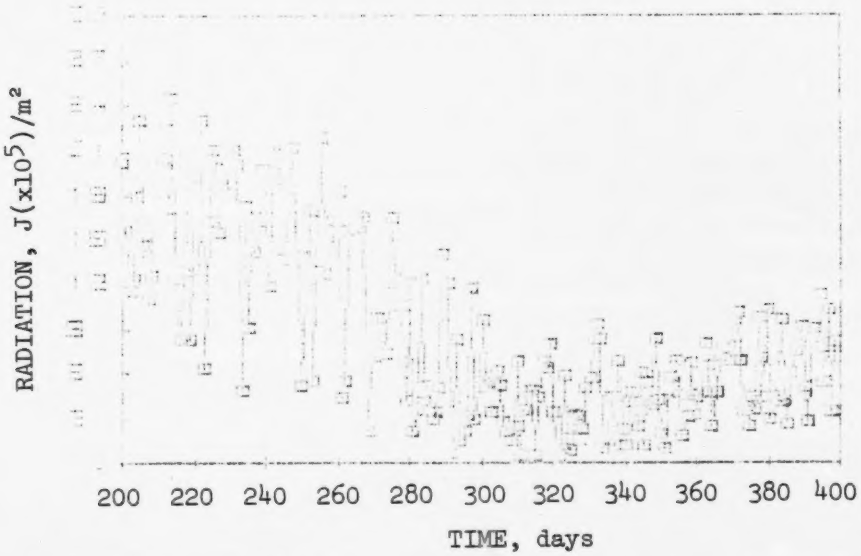

Figure C.315. (continued) Starting date of this figure is April 17, 1980.

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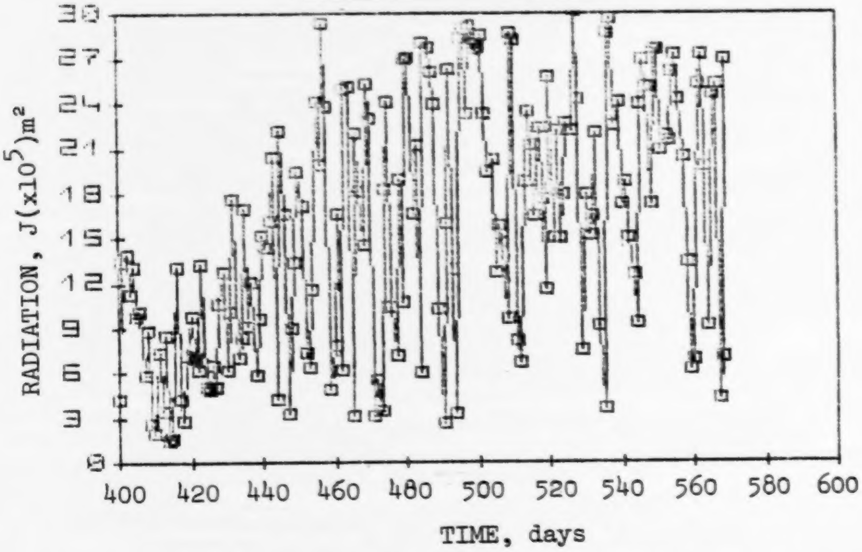

Figure C.315. (continued) Starting date of this figure is December 3, 1980.